OPHTHALMIC FACTORS
IN DYSLEXIA

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SUMMARY

Although the role of ophthalmic factors in dyslexia remains the subject of controversy, recent research has indicated that the correlates of dyslexia may include binocular dysfunction, unstable motor ocular dominance, a deficit of the transient visual subsystem, and an anomaly that can be treated with tinted lenses. These features, typically, have been studied in isolation and their inter-relationship has received little attention.

The aim of the present research was to investigate ophthalmic factors in dyslexia, with a particular emphasis on the interaction between optometric variables. Further aims were to establish the most appropriate investigative techniques for optometric practice and to explore the relationship between optometric and psychometric variables.

A pilot study was used to refine the experimental design for a subsequent detailed study of 39 children with a specific reading disability and 43 good readers, who were selected from 240 children. The groups were matched for age, sex, and performance IQ. The following factors emerged as correlates of dyslexia: slightly impaired visual acuity; reduced vergence amplitudes; increased vergence instability; decreased accommodative amplitude; poor performance at tests that were designed to assess the function of the transient visual system; and slightly slower performance at a non-verbal simulated reading visual search task.

The "transient system deficit", as measured by reduced flicker sensitivity, was significantly associated with decreased accommodative and vergence amplitudes. This links the motor and sensory visual correlates of dyslexia. Although the binocular dysfunction was correlated with increased symptoms, the difference in the groups' simulated reading visual search task performance was largely attributable to psychometric variables. The results suggest that optometric problems may be a contributory factor in dyslexia, but are unlikely to play a key causative role. Several optometric variables were confounded by psychometric parameters, and this interaction should be a priority for future investigation.

KEY WORDS: dyslexia, vision, accommodation, vergence, parallel visual processing.

to my parents

BETTINE AND ANTHONY EVANS

"I couldn't have done it without them."

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CONTENTS

PAGE

List of Figures

LIST OF TABLES

APPENDICES

CHAPTER 1
INTRODUCTION

1.1 BACKGROUND

Reading and writing are unique to man and release communication from the evanescence of verbal language. The history of written language is young, spanning some 5,000 years, whilst spoken language has probably existed for about 3-5 million years (Husain, 1986); a similar temporal distinction is apparent in ontogeny. Even today, although all human communities have a fully developed spoken language, only a minority of these languages has a written form (Liberman, 1989). For the proper development of speech, a neurologically normal child need only be placed in an environment where language is used: reading and writing typically require formal tuition. The decoding of visual symbols that are not merely representations of physical forms, but that carry phonetic as well as abstract content, makes formidable demands on any information processing system. In this context it may not be surprising that 5-10% of children have difficulties in reading Western script (Husain, 1986).

The definition, terminology, incidence, and aetiology of dyslexia are complex and controversial issues, and a brief overview of these aspects is presented in this chapter. The early history of research into dyslexia was reviewed by Hulme (1981, pp. 1-4).

1.2 DESCRIPTION AND DEFINITION OF DYSLEXIA

Dyslexia has been described as one of the most controversial topics in psychology, medicine, and education, with some scientists and educationalists still remaining sceptical about its existence (Pavlidis, 1981a). Singleton (1987) likened dyslexia to a myth, for "it seems to have some foundation in fact but has generally been nurtured by ignorance."

Rutter and Yule (1975) showed from epidemiological studies that specific reading retardation (which will be shown to equate to most definitions of dyslexia) represented more than just the lower end of a normal distribution of reading performance; its frequency significantly exceeded that predicted on statistical grounds. This finding, however, has been disputed (*see* Snowling, 1990, for a review). Dyslexia normally persists throughout life, although some individuals may develop compensatory strategies (Ingram and Dettenmaier, 1987).

Newton (1968) described dyslexia as

> "the cognitive disorder of severe reading disability. It implies difficulty in understanding and interpreting symbolic representation, especially when the symbols form an arbitrary ordered sequence. The difficulty can be present despite adequate intelligence, conventional instruction, and socio-cultural opportunities."

Miles (1984) extended this description. He suggested that dyslexia should not be thought of as difficulty with reading or even as difficulty with spelling, but that these problems were part of a wider disability that showed itself whenever symbolic material had to be identified and named.

No single definition of dyslexia is universally accepted. The one that has been most frequently quoted (Pavlidis, 1981a) is that given by the World Federation of Neurology in 1968 for "specific developmental dyslexia" (Critchley, 1970):

> "A disorder manifested by difficulty in learning to read despite conventional instruction, adequate intelligence, and socio-cultural opportunity. It is dependent upon fundamental cognitive disabilities which are frequently of constitutional origin."

Whilst several authors have adopted the World Federation of Neurology definition (e.g., Farrag et al., 1988), it has frequently been criticised, mainly on the grounds of its negative, exclusionary nature and vague terminology (Rutter and Yule, 1975; Benton, 1978; Rutter, 1978). Another vague definition was given by Jordan (1972): "the inability to process language symbols".

Witelson (1977) suggested that it was more appropriate to define dyslexia as a "specific *cognitive* deficit" than a specific deficit in reading. She felt that different subgroups may have different patterns of cognitive deficits; this point, that dyslexia represents a number of "syndromes" rather than a single disorder, is likely to exacerbate the difficulties associated with a definition.

Rutter (1978) gave 2 definitions of dyslexia. One of these was weakened by causal implications and the other defined dyslexia as an:

> "heterogeneous group of reading disabilities characterised by the fact that reading/spelling attainment is far below that expected on the basis of the child's age or IQ."

Although Rutter (1978) preferred the term "specific reading retardation" for this definition, the term "dyslexia" is, in most scientific (Vellutino, 1977; Stanovich, 1991) and lay (e.g., British Dyslexia Association) literature, virtually synonymous with Rutter's (1978) "specific reading retardation". The description quoted above has been used, therefore, as a working definition of dyslexia in the present research.

Stanovich (1991) noted that defining dyslexia by reference to discrepancies from intelligence test scores was problematic and that more basic psychometric work was needed to develop a principled method of discrepancy measurement from listening comprehension or some other verbal aptitude indicator. He also described an alternative approach of defining reading disability solely in terms of decoding deficiencies, without reference to aptitude discrepancy.

1.2.1 Terminology Associated With Dyslexia

The word dyslexia is of Greek origin and means, loosely translated, "difficulty with words" (*dys* = difficulty with, *lexis* = word) (Pavlidis, 1981a). The term was introduced by Rudolph Berlin, a renowned ophthalmologist from Stuttgart, in 1887 (Dunlop and Dunlop, 1974). "Specific learning disability" is normally used to describe people with a specific disability in one area of learning. Specific reading disability is the most common type of specific learning disability (Helveston, 1987). Naidoo (1972, pp. 98-109) criticised the use of the term "specific dyslexia" to describe dyslexia of genetic origin. She suggested that this term should be used to describe those learning disorders in which the major defect lay in learning to read, write, and spell.

Rutter and Yule (1975) noted that "the terminology used in referring to reading difficulties is chaotic and confusing". They differentiated between general reading backwardness, where reading was backward in relation to the average attainment for that age, regardless of intelligence; and specific reading retardation, which described reading difficulties that were not explicable in terms of the child's general intelligence. This terminology was widely accepted, but the further contention of Rutter and Yule (1975) that dyslexia was not synonymous with, but was a sub-division of, specific reading retardation seemed less tenable. This distinction appeared to be based on the assumption that the term "dyslexia" implied the existence of a well defined unitary condition and carried further implications concerning causality (Hulme, 1981, p. 8).

Rutter and Yule (1975) also showed that reading retardation differed significantly from reading backwardness in terms of sex ratio, neurological disorder, pattern of neuro-developmental deficits, and educational prognosis. Critchley and Critchley (1978) described children whose IQ was too low to allow them to master the task of reading as having a type of "secondary dyslexia"; reading backwardness would seem to be a less confusing term for this group.

The term "dyslexia" sometimes meets with disapproval, partly because of its misuse (e.g., for reading backwardness) and partly because some feel it carries further implications, which are poorly established, about causation and the neurological basis of the reading problem (Rutter and Yule, 1975; Rutter, 1978; Hulme, 1981, pp. 1-54). However, in line with common practice (Vellutino, 1977; Stanovich, 1991), the term "dyslexia" will be used throughout this thesis *without* these implications, i.e., synonymously with "specific reading retardation". The exception will be when describing the work of others when the terminology of the authors under review will be used.

Throughout the present work, in accordance with usual practice (Boder, 1971; Rutter, 1978), the term "dyslexia" will invariably refer to developmental dyslexia: individuals who have failed to acquire reading skills. A loss of reading skills after the initial skills have been attained is rare (Rutter and Yule, 1975) and has been termed "acquired dyslexia"; this will only be discussed where it provides a useful insight into the physiological processes involved in reading.

The literature shows that dyslexia has many synonyms. These include congenital word-blindness (Husain, 1986); strephosymbolia (Orton, 1943); developmental alexia; primary reading retardation; Gestalt blindness; and specific language disability (Boder, 1971).

1.3 DIAGNOSIS OF DYSLEXIA

The importance of accurate diagnosis of dyslexia in research was highlighted by Benton (1978): "There can be little doubt that the mass of contradictory results to be found in research literature is due in large part to the diverse and inadequate criteria used in subject selection." Boder (1971) stated that dyslexia could be diagnosed in one or more of the following ways: by a process of exclusion; indirectly, on the basis of its neurological or psychometric concomitants, or directly, on the basis of the frequency and persistence of certain types of errors in reading and spelling. Thomson (1979) decribed the diagnosis of dyslexia in a clinical setting; he stressed the "total child" context, where the results of several psychometric tests yielded an individual profile of relevant factors.

Singleton (1988) summarised the conventional methods of diagnosing dyslexia as establishing:

(a) that the child's reading age is significantly behind his chronological age

(b) that the child's intelligence is not significantly below average

(c) that there are no social, emotional, or educational causes of the reading difficulty

(d) that the child is not suffering any sight defects, hearing loss, frank brain damage, or serious problems of general health

(e) that the child exhibits some "positive signs" of the disorder, such as speech problems, difficulty with sequential memory, clumsiness, crossed laterality, etc..

Christenson et al. (1990) differentiated between specific reading disability ("generally synonymous with dyslexia") and non-specific reading disability, which could be caused by: low intelligence, educational deprivation, sociocultural deprivation, primary emotional problems, sensory impairment, poor motivation, and attentional problems. They described 3 general methods for the diagnosis of dyslexia: by excluding the above factors; indirectly, e.g., from soft neurological signs or the profile of IQ test results; and directly, by analysing the decoding and spelling patterns.

The degree of reading retardation considered necessary for a child to be diagnosed as dyslexic ranges from a basic judgement by school staff that the child could not read at the average level for his age (e.g., Goldberg et al., 1960; Legein and Bouma, 1981) to "reading at least 2.4 years below mental age" (Eskenazi and Diamond, 1983). Rutter (1978) stressed that estimates of the prevalence of specific reading or spelling retardation should specify the severity of retardation and the age group under consideration, and should be based on regression equations rather than achievement ratios (*see* Section 7.2.2.1).

1.3.1 Early Detection of Dyslexia

The early diagnosis of dyslexia facilitates effective remediation (Critchley, 1981; Singleton, 1988), and several authors have attempted to use correlates of dyslexia to develop tests that may detect the condition before reading starts. One such attempt has recorded saccadic eye movements (Pavlidis, 1985), although this approach has been criticised (Singleton, 1988). Another optometric parameter that has been suggested for the early detection of dyslexia is spatial contrast sensitivity (Lovegrove et al., 1980a). Quantitative neurophysiology may provide a marker for early identification of dyslexic children (Flynn and Deering, 1989).

1.3.2 Screening Tests for Dyslexia

Boder (1971) described a screening procedure for dyslexia that was designed to disclose the number and types of reading and spelling errors, and to enable the subject to be classified according to the author's subtypes. Miles (1982) described a simple screening test for dyslexia that was not restricted to any one group of professional workers. Several other workers have evaluated screening techniques and the predictive precursors of reading disabilites (Satz et al., 1978; Newton et al., 1979).

Christenson et al. (1991) evaluated a new screening test for dyslexia (the "TDS"); this seemed to have been developed for optometrists and to be based on spelling errors, assuming the "Boder" classification of dyslexia (*see* Section 1.6) to be correct. They evaluated the test on 52 subjects, including 10 controls; unfortunately, it was not clear whether any of the subjects had met conventional diagnostic criteria for dyslexia. Indeed, no details were given of reading or spelling ages, IQ test results, reading retardation, or even chronological ages. The study did show a reasonable correlation between the TDS and a previous, longer test (the Dyslexia Determination Test, or DDT); this is not surprising since the TDS seemed to be a simplified version of the DDT. The authors' conclusion that the TDS would allow the proper modes of therapy, optometrical and educational, to be used seemed premature: the 2 therapies are not exclusive, the test will not detect optometrical problems, and more evidence is needed before the test can be said to detect cases in need of educational therapy.

1.4 Incidence of Dyslexia

Between 1850 and 1950 the rate of literacy in Western Europe rose from 50.5% to 92% (Hulme, 1981, p. 1); a commensurate rise in reading disability is likely to have occurred. Rutter (1978) reviewed 2 large epidemiological studies in the UK that defined specific reading retardation as underachievement of at least 2 standard errors below the mean. The condition was commoner in boys than in girls, with a ratio of about 3.5 to 1. The prevalence rose somewhat in older children and there was a very marked variation according to geographical area. Specific reading retardation was found in about 10% of 10 year-olds in London, but only about 4% in the Isle of Wight. Wheeler and Watkins (1978) concluded that the male:female ratio appeared to be between 3:1 and 5:1 in most large studies.

Several authorities have given a general estimate of the incidence of dyslexia: Yule (1988) noted that severe reading difficulties that cannot be accounted for by low intelligence occur in 4-10% of children in junior schools, and Brown (1988) put the incidence between 3 and 5%.

1.4.1 International Variations

Rutter (1978) cautioned against inferences with respect to national variations because estimates were often based on noncomparable data. Farrag et al. (1988) found a relatively low incidence (1%) of dyslexia in Arab-speaking Egyptian children. They attributed this to characteristics of the Arabic language, which was written from right to left, was always written in script form, and did not have directionally confusing letters.

1.5 AETIOLOGY OF DYSLEXIA

1.5.1 Psychological and Cognitive Theories

A number of studies (e.g., Newton et al., 1979) have shown that the organisation of the cortex in dyslexic individuals has a less clear cut preponderance for verbal tasks and symbolic ordering in the left hemisphere than the non-dyslexic. They thought this predisposed dyslexic people towards "spatial" thinking abilities, whilst they tended to perform poorly at skills such as sequencing, blending sounds, and associating sounds and arbitrary symbols. This hypothesis was supported by Witelson's (1977) investigation of neural factors in dyslexia. She suggested that dyslexia was associated with bi-hemispheric representation of spatial function, in contrast to the right hemisphere specialisation observed in normal children. This bilateral representation was thought to interfere with normal left hemisphere function resulting in deficient linguistic, sequential cognitive processing and in overuse of the spatial, holistic cognitive mode.

Several other authors have linked dyslexia with a deficit in temporal or sequential processing (e.g., Naidoo, 1972, pp. 110-117; Bakker and Schroots, 1981; Pavlidis, 1981a), and Zurif and Carson (1970) felt that these were sufficiently subtle not to interfere with speech, but prevented the critical formation of spelling-to-sound correspondences and hence impaired the process of reading. A review by Vellutino (1977), however, concluded that the temporal order deficit theory was questionable.

Another feature of the theories of Newton et al. (1979) and Witelson (1977) was a deficit of left hemisphere function, and this will be shown to be a widespread view. Chasty (1979) suggested that dyslexic children had a recognisably different cerebral organisation for language that resulted in reduced language efficiency. Zurif and Carson (1970) suggested that the lateralisation of mechanisms subserving language behaviour failed to develop in dyslexia due to a maturational lag, and several other authors have conceptualised dyslexia as representing some form of incomplete maturation of the nervous system (e.g., Solan, 1966; Satz et al., 1978; Critchley, 1981). Hulme (1981) supported the maturational lag hypothesis and pointed out that this could explain the wide range of psychological correlates of dyslexia.

Legein and Bouma (1981) reviewed their visual recognition experiments and concluded that the underlying cause of dyslexia was most likely a specific recoding deficiency. Rozin et al. (1971) demonstrated that the specific nature of the coding deficit may lie in phonemic representation; this was the process of constructing whole words from their component parts on the page. Liberman et al. (1967) described how speech carried information in parallel and that phoneme perception required a special decoder. Liberman (1989) said that this subconscious "phonetic module" automatically selected and regulated the string of consonants and vowels that a spoken word comprised. There was nothing, therefore, in the child's normal experience with spoken language that necessarily acquainted him with the internal structure of words; yet this fact had to be understood for the mastering of written language. Liberman's (1989) viewpoint was summarised in his title: "reading is hard just because listening is easy".

Ellis and Miles (1978) presented experimental evidence suggesting that "the" deficiency in dyslexia involved the "name code" pathway; they suggested that the amount a dyslexic child could hold in mind in a short period was limited and as a consequence attention to detail, such as spelling, was lost. This seemed to link a coding deficiency in dyslexia with a memory deficit, and several other researchers have suggested a memory deficit in dyslexia (Hulme, 1981, pp. 52 and 173; Jorm, 1983). Hulme (1981, p. 31), however, thought that a visual memory deficit was unlikely to be a cause of reading retardation.

Singleton (1988) concluded that dyslexic children had some fundamental impairment in the cognitive systems that subserved sequential memory and phonological processing. Ellis (1991) agreed that dyslexia was caused by a deficiency in phonological processing and Snowling (1990) suggested that dyslexia was associated with phonological difficulties originating within spoken language. This view was encompassed within Vellutino's (1977) conclusion that dyslexia was best explained in terms of a "verbal deficit", which included dysfunction in the semantic, syntactic, or phonological aspects of language. This is a widely held view (Wheeler and Watkins, 1978; Hulme ,1981, pp. 52-53; Sherman et al., 1989) and Bradley and Bryant (1983) found a relationship between pre-school children's skill in categorising sounds and their eventual success in reading and spelling. Newton et al. (1979), however, stated that oral language skills were independent of dyslexia. The obvious compromise hypothesis that some dyslexic children have a speech and language disorder and some do not has also been suggested (Stackhouse and Wells, 1991, Duane, 1991).

Yet another theory suggests that individual abilities, such as auditory or visual memory, may not be deficient in dyslexia, but the fundamental deficit lies in the ability to integrate these functions (Johnson and Myklebust, 1967; Swanson, 1987); however, Vellutino (1977) and Hulme (1981, p. 35) concluded that this was unlikely. Beaumont and Rugg (1978) suggested that dyslexia might be the result of a dissociation of visual processing of verbal material from auditory speech analysis systems, owing to relative bilateralisation of visual language processing and a consequent failure of integration between the lateralised systems within the the left hemisphere.

1.5.1.1 A Model of The Reading Process

Rutter (1978) noted that reading was a complex skill that involved a number of different components and that reading difficulties may arise when any of these components was impaired. His description of these components closely correlated with the various psychological theories on the aetiology of dyslexia outlined above. Many other authorities have supported a multiple aetiology in dyslexia (e.g., Naidoo, 1972). Singleton (1987) used investigations of the various types of acquired dyslexia, resulting from injury to the adult brain, to build a model of the reading process and to identify the stages in the system most vulnerable to impairment. A modified version of this model is shown in Figure 1.1.

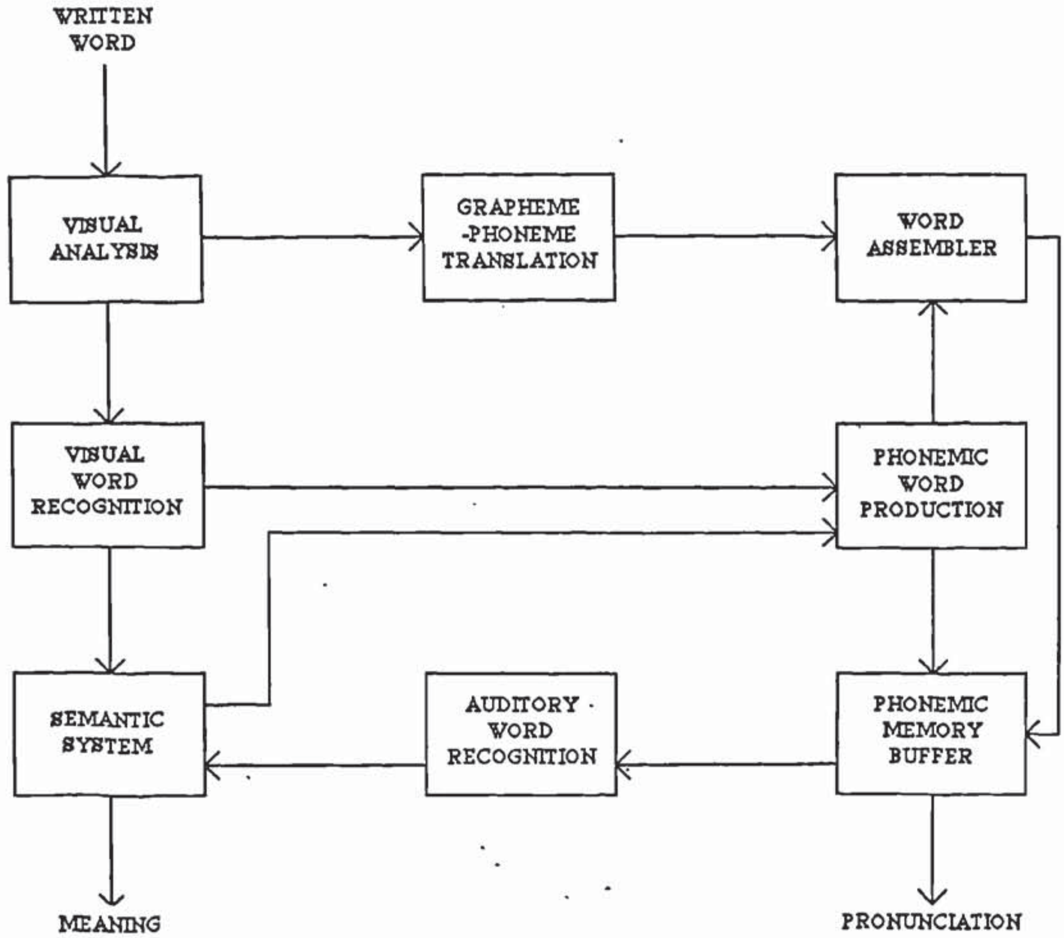

Figure 1.1 A cognitive model of the reading process; *see* text for explanation. (Adapted from Singleton, 1987).

All pathways in Figure 1.1 start with visual analysis, after which there are 2 possible paths. If the word is known in the sight vocabulary (these are the whole words that can be identified from a visual image without phonological analysis) then visual word recognition can lead directly to the semantic system and to the word production centers; alternatively, a word can be analysed in terms of its individual grapheme-phoneme units. Singleton (1987) showed that different types of acquired dyslexia can be associated with particular deficits in this model and he suggested that a similar, but less clear-cut, analysis could be applied to developmental dyslexia. This model could be used to analyse the psychological factors described in Section 1.5.1.

Swanson (1987) reviewed information processing theory and learning disabilities and concluded that it was not known whether the information processing model would prove to be valuable in this area of research. Brown (1988) argued that the various "cognitive" psychological accounts of the cause of dyslexia not only implied great heterogeneity, but that the complexity of these models implied the need for a different approach, possibly through computational modelling.

1.5.2 Genetic Influences

Most authorities accept that genetic influences do play a role in dyslexia (Beauchamp and Kosmorsky, 1987; Duane, 1991). Benton (1978) pointed out that a positive family history of dyslexia did not prove genetic determination and that hereditary factors were unlikely to account for all cases of specific reading disability. Pennington and Smith (1983) concluded that some forms of dyslexia were transmitted genetically and that there were likely to be several forms of familial dyslexia involving different modes of transmission.

1.5.3 Neurological and Neurobiological Theories

Pavlidis (1981a) reasoned that since the causes of dyslexia did not appear to result from environmental, psychosocial, or intellectual factors, the only remaining causes were constitutional. Goldberg et al. (1960) suggested that subclinical brain damage in the parietal-occipital area was a cause of dyslexia, and Jordan (1972) listed minimal brain dysfunction and minimal brain damage as synonyms of dyslexia. Frank and Levinson (1975, 1976) suggested that dyslexia was caused by cerebello-vestibular dysfunction, although this theory lacked rigorous evidence.

Orton (1943) noted that some children with reading difficulties had an inability to differentiate "b" and "d", read many words in reversed order, and had an unexpected ability to read and write reversed text. He proposed that such cases represented a physiologic deviation owing to a failure to acquire the normal pattern of complete dominance of one hemisphere, and that this was often associated with crossed (e.g., right handed and left eyed) or ambivalent dominance (*see* Section 3.2.2. In the past some researchers supported the contention that hand-eye dominance disorders were a cause of dyslexia (e.g., Benton et al., 1965, 1968), but there is now considerable evidence that reading difficulties are not usually associated with any particular pattern of handedness, eyedness, or footedness (Spitzer et al., 1959, Benton, 1975; Rutter, 1978). Hulme (1981, pp. 28-29) stated that reversal errors were not a disproportionately common type of error in reading retardation, but were simply more noticeable among a host of less easily defined errors.

Naidoo (1972) found no greater incidence of birth anomalies in dyslexia. Benton (1975) concluded from a major review that a neurological basis for developmental dyslexia had not been established because the empirical evidence was inconsistent and circumstantial. A major reason for this was thought to be the heterogeneous nature of dyslexia. He did feel, however, that the evidence suggested that there were neurological factors, as yet unidentified, that were often operative in dyslexia.

Wilsher (1991) reviewed the "medical" treatment of dyslexia, including megavitamins, antihistamines, psychostimulants, and nootropics. He concluded that most of these methods relied upon the replacement of deficits that had not been proved to be aetiologically significant in dyslexia. He further stated that no treatment offered a "cure", although the use of nootropics, that were based on the neurotransmitter GABA, was an interesting development.

1.5.3.1 Anatomical Theories and Evidence

Wada et al. (1975) noted that the human brain was unique in the functional asymmetry that existed between its 2 cerebral hemispheres. They reported the results of morphological observations on 100 adult and 100 infant brains with particular attention to the planum temporale and frontal operculum. They found that the left planum was always present, but the right planum ranged in size from absent (10%) to larger than the left (about 10%); females predominated in the latter group. They stressed that this morphological asymmetry occurred before speech developed and differed between the sexes.

Hier et al. (1978) analysed the computerised brain tomograms of 24 dyslexic patients. Ten patients showed a reversal of the normal pattern of asymmetry so that the right parieto-occipital region was wider than the left; this was significantly more than would have been predicted by chance when the effect of handedness was controlled for. These

10 patients had a lower mean verbal IQ than the other subjects. The authors thought that the reversal of asymmetry may have resulted in language lateralisation to a cerebral hemisphere that was structurally less suited to support language function and thus acted as a risk factor for the development of reading disability.

Geschwind and Behan (1982) found that left-handedness was associated with immune diseases (including myasthenia gravis), migraine, and learning disorders (dyslexia and stuttering). They suggested that in the developing foetus testosterone slowed neuronal development in the left hemisphere, whilst simultaneously damaging the development of the immune system. Conversely, they suggested that genes that controlled immune responsiveness also may regulate testosterone effects. Their theories could explain the increased incidence of dyslexia in males.

Geschwind and Galaburda (1985) described several facts that supported their hypothesis, including superior right hemisphere function in dyslexia. The planum temporale, which was the upper surface of the posterior portion of the left temporal lobe, was larger in the left hemisphere where it constituted a large portion of the temporal speech region of Wernicke, and may therefore have accounted for the usual predominant localisation of speech to the left hemisphere. Asymmetry was also found in the foetal brain where the left hemisphere matured later than the right, and the male brain matured later than the female. Geschwind and Galaburda (1985) also noted that, as the brain developed, neurons were formed in excess and many died when they failed in the competition to form connections. They briefly reviewed the evidence for a relationship between hormones and patterns of cerebral dominance. Galaburda and Kemper (1979) had found an abnormal pattern of cytoarchitecture, virtually confined to the left hemisphere, in a severely dyslexic person. Geschwind and Galaburda (1985) described evidence for a predominance of men among cases of autism, dyslexia, stuttering, and other developmental disorders; and higher rates of immune diseases, dyslexia and stuttering in strong sinistrals.

Behan and Geschwind (1985) reported studies suggesting that dyslexia can be associated with congenital lesions of the cardiovascular system and probably also of the skeletal system. They acknowledged the importance of genetic factors in dyslexia, but pointed out that the intra-uterine environment can play a major role in determining the course of development of the nervous system.

Sherman et al. (1989) described autopsy studies on 6 male dyslexic brains that had demonstrated the absence of the usual pattern of cerebral asymmetry of the planum temporale, and focal developmental abnormalities of cortical architecture, particularly in the left hemisphere's perisylvian regions. They suggested that their findings could cause dyslexia and linked them to Geschwind and Behan's (1982) theory. They pointed out, however, that this theory could not reconcile the increased incidence of immune disorders in females with the more frequent expression of dyslexia in males.

Hynd and Semrud-Clikeman (1989) reviewed investigations into brain morphology in dyslexia. Methodological deficiences were shown to weaken this literature and to preclude firm conclusions, particularly concerning the hypothesised link between handedness, auto-immune disease, and brain morphology in dyslexia. Duane (1991) reviewed a study that had used magnetic resonance imaging to support the existence of symmetry in the posterior cerebral hemispheres in dyslexia.

Critchley and Critchley (1978) and Critchley (1981) felt that dyslexia should not be confused with learning disabilities resulting from dysfunction owing to structural lesions of the brain. The extremely subtle cytoarchitectonic changes found by Sherman et al. (1989) would suggest that, with modern techniques, this distinction is no longer tenable. Pirozzolo and Hansch (1982) reviewed the neurobiology of developmental reading disorders. They noted that dyslexia was not an homogeneous clinical entity, that the aetiology of minimal brain dysfunction was also diverse, and suggested that an alteration in synaptic function may be a key to the learning problems of dyslexic children. Hughes (1982) concluded from a review of studies using the electro-encephalogram (EEG) to investigate reading disorders that there was no single causal defect in dyslexia, but a multiplicity of defects or lesions.

Singleton (1988) suggested that the dysfunction of the left hemisphere that the above theories may predict could account for the inferior performance of dyslexic children at the processing of sequential stimuli and in serial memory tasks. Duane (1991) concluded that biological mechanisms were the underlying cause of dyslexia, although he felt that the cortical dysgenesis that Galaburda's team had discovered could be caused directly by genetic influences, without the implication of testosterone.

1.5.4 Visual Theories

Several authorities have postulated that dyslexia did not in general reflect a peripheral perceptual deficit of any kind (Critchley, 1964; Critchley, 1981; Brown, 1988); some that it was not associated with any type of ocular or visual problem (Wheeler and Watkins, 1978; Helveston, 1987; Watkins, 1991); while others have felt that the literature was inconclusive (Dearborn and Anderson, 1938; Benton, 1975). Hulme (1988) thought that low-level visual processing deficits were a non-causal correlate of dyslexia; and others have suggested that visual factors played a major causative role in dyslexia (Benton et al., 1968; Irlen, 1983; Stein and Fowler, 1985; Raymond et al., 1988; Rounds et al., 1991; Stein, 1991a; MüHlendyck, 1991).

Dunlop and Dunlop (1974) believed that a narrow vertical strip of retina from each eye was represented in both hemispheres and that laterality problems with respect to this area could cause visual confusion in dyslexia. Stein and Fowler (1984) hypothesised that dyslexia could be caused by poor visuomotor control owing to the perceptual problem of not knowing where the eyes were pointing whilst reading. Stein et al. (1988) linked this theory with those of Galaburda and Geschwind (*see* Section 1.5.3.1 to suggest that disordered hemispheric specialisation lead to poor visuomotor control, which was associated with reduced vergence amplitudes. Husain (1986) noted that this theory was not exclusive; it did not account for "non-visual" reading problems.

Yule (1988) refuted the theories of Stein and Fowler (1981, 1982, 1985), cautioning against confusing correlation with causality. He claimed increasing consensus that language difficulties were more important than visuomotor difficulties as causes of reading difficulties.

It has been suggested that unstable saccadic eye movements may be a cause of dyslexia (Prechtl, 1962; Frank and Levinson, 1973; Stein and Fowler, 1984), although several authors have disputed this and associated therapies, often arguing that unstable eye movements were the effect rather than the cause of reading disabilities (Goldberg and Arnott, 1970; Lefton et al., 1978; Adler-Grinberg and Stark, 1978; Benton, 1978; Rutter, 1978; Critchley, 1981; Pirozzolo and Hansch, 1982; Blackwell et al., 1983; Levine, 1984; Beauchamp and Kosmorsky, 1987).

Riding and Pugh (1977) suggested that reading disability could be caused by unusually long or short persisistence of the visual icon. Lovegrove et al. (1986a) reviewed the evidence for a deficit of the transient visual system in dyslexia and suggested several ways in which this could cause reading retardation. One possible involvement of a transient system deficit in reading is if inputs from successive fixations became superimposed (*see* Section 2.7.1.4. This may result in inconsistent information about the spatial arrangement of the letters (Lovegrove et al., 1990) and could provide a link with Stein and Fowler's (1984) theory.

Other visual problems that have been suggested as causes of dyslexia included a perceptual syndrome that could be treated with tinted lenses (Irlen, 1983); and accommodative dysfunction, heterophoria, low vergence amplitudes, hypermetropia, astigmatism, and aneisokonia (reviewed by Evans and Drasdo, 1990).

If dyslexic children have difficulty interpreting written language owing to a visual deficit then they should not experience difficulties with the spoken word (Beauchamp and Kosmorsky, 1987). The normality or otherwise of oral language skills in dyslexia remains the subject of some controversy (*see* Section 1.5.1).

1.5.5 Miscellaneous Theories

1.5.5.1 Social Factors

Benton (1978) and Rutter (1978) pointed out that some factors, such as geographical area, family size, socioeconomic status, the cultural values of the community, and temperamental characteristics, were systematically associated not only with general reading backwardness but also with specific reading disability. Rutter (1978) also noted that reading difficulties were associated with low birthweight, but to a much lesser degree than intelligence. Naidoo (1972) found no greater frequency of mother/child separations in dyslexic children than normal. Critchley and Critchley (1978) stated that dyslexia occurred in all social groups but, because good disgnostic facilities were not always available, it may not be correctly identified, especially at "the lower end of the social scale".

1.5.5.2 Automaticity

Eakin and Douglas (1971) defined automatised behaviours as ones that have been so highly practiced as to require a minimum of conscious effort for their efficient execution. They reviewed the literature on this subject and described some experimental work using a battery of cognitive tests that were designed either to be dependent upon or independent of automatisation skills. Sixteen children with a mild degree of specific reading disability performed significantly worse than 16 age and IQ matched controls at the "automatised" tasks, but not at the others. These authors felt that the essential nature of automatisation tasks could be conceptualised in 2 ways. Firstly, as a highly practised behaviour attaining a limit of learning after which they were elicited automatically, and secondly as a sequencing skill.

Nicolson and Fawcett (1990) compared the performance of 23 dyslexic children, aged 13 years, with age- and IQ-matched controls with a dual task paradigm; subjects performed each test twice, once as a single task, and once as a dual task concurrently with a secondary task. The primary task involved balancing on a beam and the 2 secondary tasks were counting backwards and an auditory choice reaction task; these were calibrated so that each subject found them equally difficult. The dyslexic group performed significantly worse under dual task conditions, but not under single task conditions. The authors explained their results in terms of an automaticity deficit in dyslexia, and suggested that many of the reading deficits of dyslexic children were merely symptoms of a failure to fully automatise skills. Nicolson and Fawcett (1990) suggested that genetic endowment, practice, and intelligence allowed dyslexic children to achieve mastery of most skills.

Eakin and Douglas (1971) listed walking, talking, reading, and writing as examples of automatised behaviour; this must raise questions concerning the hypothesised causative link between deficient automatisation and *specific* reading retardation. It seems unlikely that such a general and pervasive deficit as the automaticity hypothesis would suggest (Nicolson and Fawcett, 1990) could allow normal performance at a wide range of everyday tasks (e.g., driving).

1.5.6 Conclusion

The wide range of theories on the aetiology of dyslexia reflect the observation that "it would be difficult to find a task on which reading-disabled children have not been reported to be deficient" (Benton, 1978). Pennington and Smith (1983) stated that a disorder such as dyslexia held out the long-term prospect for being understood at all levels of analysis, including the genetic, neurobiological, neuropsychological, environmental, and functional. More work is needed at all of these levels, but the above outline of the aetiology of dyslexia emphasises the heterogeneous nature of this condition; this is now acknowledged by most authorities (Naidoo, 1972, pp. 98-109; Mattis et al., 1975; Brown, 1988). If optometric correlates of dyslexia are considered within this framework, then *if* they play a causative role this is likely to be in conjunction with non-visual factors (Solan, 1966).

1.6 CLASSIFICATIONS OF DYSLEXIA

Benton et al. (1968) felt that most cases of dyslexia could be classified into 3 categories: visuo-motor, where hyperactivity was the predominant feature; visuo-auditory, characterised by weakness with phonics; and visuo-optic, which was characterised by reversals in reading and spelling. Although this classification was based on a large population, there may have been a referral bias since all the subjects had consulted an ophthalmologist. Johnson and Myklebust (1967) and Jordan (1972) differentiated between auditory and visual dyslexia according to the nature of the deficit. The former condition was characterised by an inability to auditorise and the latter as: an inability to visualise, visual discrimination difficulties, and visual memory disorders.

Boder (1971) proposed that all dyslexic children could be classified according to one of 3 reading-spelling patterns; she said that none of these patterns had been found in normal readers. Dysphonetic dyslexia was characterised by a child who read words globally, as instantaneous visual wholes from the limited sight vocabularly, rather than analytically; and as a result could not cope with new or unusual words. The opposite was dyseidectic dyslexia, exemplified by the analytic reader who could not perceive letters or words as visual wholes and who consequently read laboriously and could not deal with words that were irregularly spelled or pronounced. The final group, mixed dysphonetic-dyseidectic dyslexia-alexia, comprised children with the combined deficits of both groups; they were usually the most severely handicapped educationally. Flynn and Deering (1989) used an EEG technique to demonstrate increased left hemisphere acitivity in dyseidectic children (compared to those from the other subgroups) during visuo-spatial tasks and reading.

Naidoo (1972, pp. 98-109) investigated subgroups in 94 dyslexic boys using a cluster analysis on data from developmental, psychometric, neurological, and familial variables. The results did not not support the concept of clearly defined subgroups but suggested that there may be one main group with a maturational lag, another with a language disability of genetic origin, and 2 smaller groups. One of these showed evidence of a cerebral insult, visuo-spatial and visual retention deficits, and indiscriminate hand and foot preference. The final sub-group also had poorly established laterality, but associated with minor neurological signs and a familial tendency.

Mattis et al. (1975) used a battery of neuropsychological tests to classify dyslexia into 3 syndromes: language disorder; articulation and graphomotor dysco-ordination; and visuo-perceptual disorder. Hulme (1981, p. 20) supported the existence of a group of retarded readers whose problems stemmed from a language disorder, and another smaller group whose difficulties were of a visuo-perceptual type.

Rutter (1978) pointed out that although reading difficulties appeared to have many causes it was less clear whether this also meant that there were several distinct and different syndromes of reading disability. He noted that numerous investigations had indicated that dyslexic children could be subdivided into 3 groups: those with mainly language, mainly articulation, or mainly visuospatial problems. He believed, however, that there was an appreciable overlap between the groups and many children did not fall into a definable category. Rutter (1978) concluded that attempts to differentiate specific reading retardation into seperate syndromes on the bases of cognitive pattern; types of spelling error; genetic background; or presence or absence of brain damage, psychiatric disorder, or social disadvantage were all fraught with problems. Brown (1988) argued that dyslexia was so heterogeneous that it defied classification. Miles (1991) reviewed the evidence concerning the Johnson and Myklebust (1967) and Boder (1971) classifications and concluded that the visual/auditory dyslexia distinction was not valid. He criticised the assumption that any weakness on a visually presented psychometric test was necessarily connected with that modality, and noted that reading and writing were multisensory activities in which the senses could support and interact with each other.

Singleton (1987) used investigations of the various types of acquired dyslexia, resulting from injury to the adult brain, to build a model of the reading process and to identify the stages in the system most vulnerable to imairment. Lubs et al. (1988) described a study that was in progress to identify inherited subtypes of dyslexia and to characterise these by specific genetic and other diagnostic techniques including PET scanning, MRI, and behavioural tests.

Christenson et al. (1990) believed that there were 3 basic types of dyslexia. Dyseidesia, was said to be caused by dysfunction of the angular gyrus of the left parietal lobe and resulted in impaired "whole word" coding. Dysphonesia was thought to be caused by dysfunction of Wernicke's area of the left temporal and parietal lobes and resulted in impaired phonetic coding. Finally, dysnemkinesia was claimed to be caused by dysfunction of the motor cortex of the frontal lobe (left hemisphere for right handers) and to result in impaired motoric memory of letter formulations, which was said to contribute to a high frequency of letter reversals. This theoretical paper contained little evidence to support this classification, particularly the final subgroup. Unfortunately, some authors (e.g., Christenson et al., 1991) have assumed that classifications of dyslexia were unequivocal and rigid and have based screening tests and treatment regimens upon them.

1.7 SYNTHESIS OF A HYPOTHESIS OF THE AETIOLOGY OF DYSLEXIA

Recent evidence has been described that suggests a neurobiological cause of dyslexia, involving subtle lesions at many cortical sites, mainly in the left hemisphere (*see* Section 1.5.3.1). In the cases that have been studied to date, idiosyncratic combinations of these sites have been affected in each dyslexic person, and it is seems likely that some correlates of dyslexia represent functional corollaries of these structural abnormalities. This could explain why these correlates are inconsistently associated with dyslexia, and this condition may represent a syndrome where a variable number of these factors are present in a given sufferer. Although many of these factors may contribute to the reading disability, it would seem likely that some are non-causal correlates. This model could also explain the heterogeneous nature of dyslexia, which would be compounded by cases who did not manifest the "dyslexic syndrome", but represented those poor readers with normal IQ that would be expected to occur by chance in a normal population.

1.8 THE EFFECT OF PATHOLOGY ON READING ABILITY

When considering how significantly ocular problems might contribute to dyslexia, it is relevant to consider the effect of visual loss through ocular pathology on reading ability. Warrington and Zangwill (1957) reported a case study of a 41 year old patient who, following head trauma, acquired dyslexia. He also developed a right homonymous hemianopia, which split the macula, and was subsequently found to have a large left occipito-parietal meningioma. His eye movements were abnormal. The reading improved as his awareness of the hemianopia increased and he developed compensatory head and eye movements. The authors felt that the atypical eye movements probably resulted from abnormalities of visual perception, and that the reading disability was at least partly owing to a failure in oculomotor adjustment secondary to the hemianopia. Although no quantitative data were given, this case study suggested a causative link between the deficient oculomotor scanning mechanism (here caused by the hemianopia) and the acquired dyslexia.

Kinsbourne and Warrington (1962) described 6 patients with lesions (owing to tumours or strokes) of the right hemisphere causing left hemianopia. They suffered from a reading disability whereby they guessed the left half of every word they read; e.g., *level* might be read as *novel*. When the patients were shown a word that was positioned in a tachistoscope so that it fell completely in their seeing hemifield they still only saw half the word and completed it as before; it was concluded that the reading disability was caused by a pathological alteration in the perceptual processes causing an abnormal distribution of visual attention. The authors' statement that the patients were unaware of their disability was puzzling; the subjects would surely have known that their reading was poor and the idiosyncratic nature of their errors must have been noticeable. No statistical evidence was presented.

Bodis-Wollner (1972) presented data on 2 patients with cerebral lesions, and 4 normals. Eye examination results were said to be normal (no details were given), although unspecified visual field defects were mentioned. Both subjects had difficulty reading, and abnormal contrast sensitivity functions (CSF's), despite normal visual acuity. Bodis-Wollner (1972) attributed the reading defect to an effect of size-tuned channels in the visual system.

Hartje (1972) reviewed the effect of neurological oculomotor disorders on reading, and described subjects with severely reduced visual acuity owing to nystagmus who were unable to read until injected with barbital. Another case compensated for a failure of saccadic eye movements by jerking his head with an accompanying blink during reading; this may demonstrate the need to take in information in discrete parcels. In oculomotor apraxia the harder the patient tried to turn his eyes, the more he was unable to do so, although full random movement of the eyes may be possible. Hartje (1972) reported that this condition often resulted in reading difficulties, and in one case was associated with an absence of convergence and accommodation. Spasmodic fixation was described as the condition when a patient's eyes tended to remain fixed on any point in central vision and could not be moved voluntarily unless the retinal afferences were interrupted. This "pathologically-exaggerated fixation reflex" meant that the eyes were only able to fixate a slowly moving stimulus or along closely arranged dots and was said to result in a fairly typical reading difficulty.

Hartje (1972) described "failure of fixation" as an oculomotor disorder that was complementary to spasmodic fixation and occurred when the patient had difficulty in keeping his eyes fixed on any object outside their resting position. This had often been considered to result in reading disability. The author next described a feature of Balint's syndrome called psychic paralysis of gaze where, during fixation, a subject had an inability to direct the gaze towards a point in the peripheral field of vision. This condition could be described as a combination of failure and spasm of fixation, and was also often associated in the literature with a reading disorder. Hartje's (1972) review concluded that although some cases of reading disability were primarily owing to an eye movement disorder it was not easy to determine to what extent such a disorder was the cause or the result of a reading disturbance. This problem was not resolved by eye movement recordings, although the author suggested that examination of eye movements on more elementary levels of function may be revealing. In view of the severe neurological problems that this paper described, the statement that "the optokinetic functions must be grossly defective in order to produce a reading disability" was not surprising. This must, however, weaken the arguments of those who claim that subtle eye movement disorders play a causative role in dyslexia. This paper only considered version movements, did not always clearly differentiate between congenital and acquired conditions, and did not consider the possibility that some of the cases in the literature could have resulted from a visual conversion reaction.

Cummings et al. (1985) evaluated the reading eye movements of 36 adult eyes with a central scotoma from various retinal diseases. Visual field data were combined with eye movement recordings to determine which area of the visual field the patient was using for fixation. The authors found that 72% of their patients habitually used 1 area of the retina for fixation, although some used 2 areas. The remainder of the patients had not developed a single preferred viewing angle. The reading rate diminished with log size of central scotoma (r = -0.67), although the accuracy of symbol or word recognition did not significantly alter, even with central scotomata up to about 20° in diameter.

Ciuffreda et al. (1985) examined the eye movements of 4 patients suffering from Friedreich's ataxia, congenital dyslexia, hemianopia with acquired dyslexia, and quadrantopia during the tasks of following a moving dot, reading dots, and normal reading. The patient with Friedreich's ataxia made frequent saccadic intrusions, although less so when reading print. The third patient had had neurosurgery at the age of 17 subsequent to a subarachnoid haemorrhage. This had left him with right homonymous hemianopia (with macula sparing), acquired dyslexia, and specific perceptual deficits. He was thought to have a problem in visual reception and poor visual sequential memory. Saccades into the seeing hemifield were accurate, but saccades into the blind hemifield were generally inaccurate, often with large (approx. 5°) dynamic overshoots. Predictably, his pursuit movements showed more corrective saccades when tracking the target toward the blind field. Reading was slow, with an excessive number of progressive saccades of small amplitude, often with abnormally large dynamic overshoots. The return-sweep saccade was generally hypometric, although mean fixation duration was normal, as was the mean regression level.

Ciuffreda et al.'s (1985) fourth patient had, at the age of 24 years, undergone neurosurgery to repair a spontaneous intracerebral haemorrhage in the left posterior temporal lobe. This resulted in an upper right homonymous quadrantanopsia (with macula sparing), severe aphasia, and total alexia. Fixational, saccadic, and pursuit eye movements were all within normal limits. Reading of dots and easy text was normal, but with unfamiliar text there was an increased number of fixations, producing an abnormally slow reading rate. This was thought to result primarily from the residual, post-traumatic brain dysfunction, presumably including the language processing centres, rather than the field defect.

Drasdo (1988b) briefly described a hemianopic patient with "pseudo-dyslexia". The most significant ocular factor contributing to the reading disability was not the hemianopia (which was in the left hemifield) but was poor accommodation.

Bailey et al. (1988) presented an abstract of their study of the effect of age-related maculopathy (ARM) on reading ability. Eye movements were monitored while subjects read word and text charts that contained a wide range of print sizes. The ARM subjects made similar fixation pauses to normals, but had smaller perceptual spans and made more regressions. Luminance levels had a larger effect than normal, particularly on perceptual span, but did not influence fixation duration and regression rates.

Beauchamp and Kosmorsky (1989) described the neural systems that moved the eyes during reading, but pointed out that these systems did not have to be functioning properly for normal reading to be possible. They gave the examples of: albinism, chronic progressive external ophthalmoplegia, subnormal visual acuity, and nystagmus as disorders that seriously compromised vision or ocular motility without impairing reading. They did not discuss the role of compensatory strategies in overcoming these problems.

1.8.1 Conclusion

Care should be taken in extending findings for experienced readers who develop an abnormality to those who were born with an abnormality. The evidence in this review, however, suggests that although severe ocular or cerebral pathology may slow the reading rate, it does not necessarily seem to cause the excessive reading and spelling errors that are characteristic of dyslexia.

CHAPTER 2

A REVIEW OF OPTOMETRIC CORRELATES OF DYSLEXIA

2.1 INTRODUCTION

The terminology used in this review is taken from the paper under description. Reading disability and reading disabled will be abbreviated to RD and visual acuity to V/A. Since dyslexia is normally included under the generic heading of learning disabilities, key studies of learning disabled children will be included. Research on accommodation will be included in the section on binocular vision anomalies.

Most of the optometric tests in the review chapters are explained in Chapters 6 and 7, and some of the psychometric tests are described in Chapters 5, 6, and 7. Where unique or very uncommon tests have been used, these will be described in the review. For a description of other optometric tests that are referred to in the review chapters, the reader is referred to Millodot (1986), and for the psychometric tests to Sweetland and Keyser (1983).

2.2 PREVIOUS REVIEWS

Witty and Kopel (1936) concluded that the following problems, singly or in combination, were unrelated to reading deficiency: slow fusion, no fusion, lateral muscle imbalance, deficient acuity, and ametropia. They felt, however, that these visual factors could contribute to poor reading in individual cases and that eye examinations were an important part of the management of reading disability.

Robinson and Huelsman (1953) noted that previous research in this area was subject to one or more of the following limitations:

"1. Assumptions have been made that the visual screening tests used were both reliable and valid.
2. Assumptions have been made that the norms for the tests used are adequate. In some instances adult norms have been applied to children.
3. Visual characteristics other than those included in existing visual screening tests have generally not been considered.
4. The subjects from which data were collected have not been adequately described.
5. Sampling errors appear to limit the applicability of some conclusions.
6. Results were based upon as few as nine or ten subjects.
7. Identification of good and poor readers has been made when intelligence tests which required reading were used as a means of measuring reading expectancy. This practice is questionable for poor readers.
8. The statistical analysis of data has been inadequate to determine whether differences and similarities resulted from chance."

Many of these criticisms are just as relevant for research today as they were 35 years ago. The authors concluded that there was inconsistent evidence for a relationship between visual efficiency and reading progress.

Huelsman (1953) reviewed several studies, many of them carried out by Eames, and concluded that the following defects are probable factors in reading disability: exophoria, hypermetropia, poor stereopsis, aniseikonia, amblyopia, premature birth, and fatigue. She suggested several implications for teaching.

Vernon (1957) reviewed the relationship between various visual defects and reading disability. A summary of this review is given in Table 2.1.

RESEARCHER	DATE	OPHTHALMIC CORRELATES	INCIDENCE
Eames	1932	exophoria & hypermetropic astigmatism	?, 114 RD,146 controls
Selzer	1933	eye muscle imbalance & poor fusion (unsystematic study)	90% of a few RD (9% of 100 controls)
Witty & Kopel	1935	slow fusion	29% of 100 RD 1% of controls
Eames	1935	exophoria	63% of RD : 16.7% of controls
		hypermetropia	53% of RD : 27.6% of controls
		low fusion	44% of RD : 18% of controls
		(TOTAL NO. IN STUDY:	100 RD & 143 controls)
Fendrick	1935	binocular acuity	48% of RD : 23% of controls
		astigmatism	42% of RD : 23% of controls
Wagner	1936	fusion, acuity, poor stereopsis	not significant
Farris	1936	hypermetropia & strabismus	caused less gain in reading over 1 yr, helped by lenses
Dearborn & Anderson	1938	aniseikonia	51% of RD : 23% of controls
		(TOTAL NO. IN STUDY:	100 RD & 100 controls)
Spache	1940	exophoria & aniseikonia	total of 50 RD in study
Wolfe	1941	astigmatism	?
Macmeeken	1942	strabismus	?
Schonell	1942	strabismus	4% of RD: 0.2% of controls
		hypermetropia or astigmatism	22% of RD : 15.5% of controls
Park & Burri	1943a	'total eye defect score'	correlation co-effic.: 0.465
		'total duction score'	0.647
		exophoria	0.631
		(TOTAL NO. IN STUDY:	225)
Park & Burri	1943b	fusion, stereopsis, duction, poor V/A	? : total in study: 11 RD
Robinson	1946	poor duction	20 of 30 RD
		high phorias	> half of 30 RD
		hypermetropia	?
Park	1948	heterophoria	45% of 133 RD
		poor conv., accomm., & stereopsis	"frequent"
Eames	1948a	hypermetropia	43% of RD: 12% of controls
		exophoria	"more frequent"
		(TOTAL NO. IN STUDY:	1000 RD & 150 controls)

Table 2.1 Summary of Vernon's (1957) review. The "ophthalmic correlates" column describes the visual problems that the researcher(s) were said to have found in their RD subjects, and the incidence column gives, where quoted, any quantitative evidence or the total number of subjects in the study. "conv." means convergence, and "accomm." means accommodation.

Vernon (1957) summarised that it is not clear what proportion of reading disability is due primarily to ocular defects, although she thought that such defects could affect reading and should therefore be corrected as soon as possible, particularly in older children who read smaller print. She believed that even small degrees of muscular imbalance were significant and noted that orthoptic training may help.

Eames (1959) reviewed his studies on 3,500 children who had been referred to him, half with reading disability. He has a unique multi-disciplinary approach, being an ophthalmologist and a educationalist. Unfortunately, his sample is likely to be affected by a referral bias: patients referred to an eye care practitioner are more likely to have visual problems than those who are not. His findings, which were not subjected to statistical analysis, will be described below.

Critchley (1964) succinctly and comprehensively reviewed all aspects of dyslexia. He believed that severe brain damage might cause death, whereas increasingly milder damage might lead to cerebral palsy, epilepsy, or dyslexia; such cases were said to differ from, and to be rarer than, developmental dyslexia. This term was reserved for poor readers who had difficulty learning the meaning and sound of verbal symbols; although neurologically sound their problem was said to be constitutional in origin. Critchley (1964) concluded that developmental dyslexia was not associated with anisometropia, oculo-motor anomalies, or field defects, and was probably not associated with colour vision defects. He said that abnormal eye movements were an effect, rather than a cause of dyslexia, and thought the results of visual perception experiments to be equivocal.

Weisbach (1965), in describing the ophthalmologist's role in dyslexia, included a review of some of the literature. He listed many causal factors, including hyperopia, aniseikonia, fusional irregularities, and visual immaturity; hemianopia was also described as a common finding in dyslexia. He went on to describe how an ophthalmologist should diagnose a dyslexic and detailed treatment and prognosis. This review mainly comprised the author's opinions; no results or statistical evidence were given, and very few studies were cited.

Solan (1966) reviewed "some physiological correlates of dyslexia". He suggested that the most significant anomaly was an inability to change or sustain accommodation, which was usually accompanied by low divergence. It was also hypothesised that excessive activity of the sympathetic nervous system could cause hyperactivity, reduced accommodative control, and mydriasis resulting in photophobia. The role of visual training in such cases was briefly described. The author's views were not supported by data or references.

Shearer's (1966) review concluded that the following ocular problems were factors in dyslexia: hypermetropia over 1 D, poor convergence, and exophoria at near. He thought that myopia and stereopsis were definitely not factors; whilst V/A, astigmatism, and ocular dominance were unlikely to be factors. He was uncertain about the relevance of decreased visual fields, aniseikonia, and the controlling eye; and felt that fusional abilities were not significant because the tests were too subjective. He surmised that visual problems were not a major cause of poor reading, although accommodative and convergence fatigue may be related to reading performance.

Robinson (1969) concluded that V/A was not related to reading disability, although it is not always clear whether she was referring to vision (unaided) or V/A (optimally corrected). Hypermetropia was found to be related to reading disability; myopia, on the other hand was thought to help reading and possibly be caused by excessive reading; this was a relatively common view at that time. Astigmatism and poor binocular co-ordination were felt to be possible correlates of reading disability. Visual fields and "blind spots" were also thought to be possible correlates, although the author's interpretation of these terms was not defined. An interesting finding was that aniseikonia, particularly when over 1%, was related to reading disability. Robinson (1969) concluded that eye examinations were important since the correction of defects may allow a child to read with less discomfort.

Kauffman (1969) felt that near point visual dysfunction was a significant cause of poor school achievement. He quoted a few studies as evidence, but most of his views seem to originate from his own, unpublished, observations. A paper by Smith (1970) was also based on personal, mainly anecdotal observations. He felt that reading and learning disabilities were closely related to visual perceptual skills and, although he linked reading difficulties to subtle defects of accommodation, convergence, binocular orientation, and spatial localisation, he was critical of "motorically based" training procedures (*see* Section 2.6.2).

Watts (1970) pointed out that visual defects in retarded readers may: have no effect on reading at all; may be causally associated with the reading retardation or may complicate an existing adverse factor; or may be non-causally associated with reading retardation. His thorough review of the literature is summarised in Table 2.2.

Wold (1971) stated that "the eye and eye deviations correlate very low with reading difficulties" and suggested, from his own experience, that learning difficulties were associated with several visual factors, especially poor binocular co-ordination.

DATE	RESEARCHER	OPHTHALMIC CORRELATES	INCIDENCE
1932	Eames	exophoria at near	?
1933	Selzer	eye muscle imbalances	all
1934	Crider	eye muscle imbalance in one eye	?
1934a	Eames	"eye defects & fusional deficiences"	? (from 28 Ss in study)
1934b	Eames	poor fusional convergence	? (from 88 RD & 52 cont.)
1935	Clark	abnormal vergence movements at beginning and end of line	? (11 Ss in study)
1936	Betts	reading disability is multifactorial	?
1935	Fendrick	none	from 64 RD & 64 controls
1936	Gates & Bond	no eye and hand dominance correlation	from 65 RD & 65 controls
1936	Witty & Kopel	not a main cause of reading disability	from 100 RD & 100 controls
1936	Farris	myopia leads to better reading	from 384 RD & 384 controls
1937	Wagner	confusing results with Betts Ready to Read cards (BRTRC)	760 Ss in study
1936	Buswell	none with BRTRC visual efficiency test	?
1938	Dearborn & Anderson	aniseikonia significantly correlated, but stress multifactorial aetiology RD	? (from 100 Ss & 100 controls)
1938	Farris	not V/A. Myopia, monocularity, & muscle imbalance; may read better without lenses	? (from 384 Ss and 384 controls)
1938	Berner & Berner	crossed dominance not related to RD	?
1938	Stromberg	not hyperopia, myopia, or astigmatism	? (did use control group)
1941	Betts & Austin	RD not correlated to summation of 14 visual factors	109 Ss in study
1942	Johnston	abnorm. dominance not correlated to RD	?, statistics were used
1943a	Parks & Burri	no correlation with BRTRC, but "poorly fitted glasses cause particularly serious retardation"	11 Ss in study
1943b	Parks & Burri	no correlation of eye abnorm. with RD	?
1948	Eames	no significant correlates	from 1,000 RD & 650 controls
1953	Robinson & Huelsman	" " "	50 Ss in study
1953	Stevenson & Robinson	no correlation with stability of hand-eye dominance over 2 years	?
1959	Spitzer et al.	no correlation with mixed dominance	from 103 Ss & 288 controls
1962	Money	"ocular and optical defects are of negligible dyslexic significance"	comment on editing several papers
1963	Young	myopes better readers than hyperopes	117 Ss in study
1964	Eames	anisometropia correlated with RD	statistics questionable
1965	Dunlap	surgically treating high phoria cases led to 'good improvement'	35 Ss in study, no data
1965	Campion	visual defects are not the cause of RD but may be associated with it	? no Ss
1966	Money	"Reading under achievement seldom is secondary to ocular or optical disorders"	review only
1967	Friedman	fixation stress (similar to fixation disparity); exercises helped	from 17 RDs : no controls
1967	Rengstorff	sight. dom. correlated with reading speeds	303 Ss in study
1967	Smith	orthoptic treatment helps RD	2 Ss in study
1968	Flax	V/A & refractive error not correlated poor fusion & accomm. can contribute	?

Table 2.2 Summary of Watts' (1970) review. The "ophthalmic correlates" column describes the visual problems that the researcher(s) were said to have found in their RD subjects, and the incidence column gives, where quoted, any quantitative evidence or the total number of subjects in the study. "S" = subject, "abnorm." = abnormality, "sight. dom." = sighting dominance, and "accomm." = accommodation.

Drasdo (1972) cited the review by Flom in 1964, who noted that few publications gave any statistically significant evidence of visual defects being associated with reading retardation, despite the claims of many authors. Drasdo (1972) selected from the literature the following visual defects which have been alleged to be associated with reading problems: aniseikonia; anisometropia; anisodominance; anomalies of accommodation; astigmatism; atypical reading eye movements; choreiform eye movements; colour agnosia; colour vision defects; delayed visual readiness or maturation; equal saccadic reaction times (to R and L); fixation disparity; heterophoria; hemianopia; hypermetropia; low fusional reserves; low V/A; O.K.N. asymmetry; patterns of eye dominance or control; poor control of retinal rivalry; saccadic overshoots; suppression; visual agnosia; and visual inattention.

Hartlage's (1976) review highlighted the equivocality of the literature, which he attributed to: different sampling techniques; ambiguity in the operational definitions of vision; inconsistent criteria for determining reading impairment; the use of correlational measures in some studies and of differences between groups in others; and different subject ages. He suggested some directions for future research, stressing the need to take account of developmental factors, and interactive and bidirectional relationships among developmental vision and reading factors.

Grosvenor (1977) concluded that good reading performance is associated with myopia and poor reading performance tends to be associated with hypermetropia, astigmatism, heterophoria (mainly esophoria), poor fusional convergence, strabismus, and colour vision deficiencies. He thought that the results concerning colour vision deficiencies may be caused by some children's difficulty in understanding the test; this highlights the need for a control group that is matched for intelligence. Grosvenor (1977) pointed out that an associated factor may not be a cause, although he implied that visual problems often contribute to poor reading; he also noted a dearth of research concerning the effect of treatment of visual anomalies on reading ability, and deprecated the widespread correction of very low refractive errors (e.g., +0.50 DS). Unfortunately, this review only included literature that suggested that there *is* a relationship between visual anomalies and reading ability.

Pierce (1977) noted that the majority of studies investigating the relationship between vision therapy and academic achievement were poorly conceived, poorly carried out, and were not statistically analysed. He differentiated between the visual task for sophisticated readers and for those who were beginning to read and discussed the assessment of reading and intelligence. He pointed out that various visual factors may inter-relate so that models of compensation should be considered. He also advocated further consideration of the scales that are used in optometric measurements. He concluded from the literature that astigmatism and heterophorias were not associated with poor reading.

Hyperopia, uncorrected anisometropia, uncompensated aniseikonia, and lateral vergences were thought to be associated with poor reading. The findings concerning V/A were inconclusive, and the literature suggested that myopia was associated with better readers. The author stressed the need for studies investigating the forced vergence range for fixation disparity. This paper also reviewed vision training (*see* Section 2.6.2).

Rutter (1978) reviewed the prevalence and types of dyslexia. He included a review of visuo-spatial studies and criticised the methodology of most inter-sensory studies. The section on eye movement research was not very representative of work in this area. Rutter pointed out that many researchers have assumed, probably incorrectly, that dyslexia is homogeneous; and that this may have invalidated their results. His conclusions gave useful advice on the definition of dyslexia, methodology of studies, and future psychological research, stressing the importance of multifactorial influences.

Wheeler and Watkins (1978) concluded that minor defects of acuity, visual fusion, strabismus, and the like are not major causative features of dyslexia. The only support that was given for this statement was that the authors thought these defects to be exogenous; this would seem to be an erroneous belief. Bedwell (1980) briefly reviewed his earlier research on infant and junior school children. He had found that in children with reading disability, complex dynamic binocular visual aspects are likely to affect many aspects of reading difficulty. Barnard (1983) concluded from his review that children with learning underachievement experience a high incidence of oculomotor instability or other ocular anomalies. He noted similar findings concerning the connection between otitis media in infancy and reading disability.

Grisham and Simons (1986) reviewed the literature concerning refractive error and the reading process. They found that distance V/A did not appear to be related to reading ability, and near acuity possibly was; they highlighted the work of Bailey that showed that the reading speed of adults was reduced when print size was reduced to less than 3 times larger than the V/A. Grisham and Simons (1986) found that hyperopia was correlated with reduced reading performance, although the evidence concerning astigmatism and anisometropia was ambiguous and myopia was either unrelated, or was possibly associated with good reading; refractive correction had been shown by most workers to help reading. The authors pointed out that single factor analysis is simplistic - the effect of compensation strategies and adaptation need investigation. They also felt that stereopsis tests do not screen for refractive errors, and stated that retinoscopy should be included in future research. This paper refers to learning difficulties, not dyslexia; the authors applied a strict definition of dyslexia, believing that it is a neurological problem.

They also made the important point that the effect of a prescription on reading may be an indirect one through it's effect on binocular function.

Simons and Grisham (1987) reviewed the subject of binocular anomalies and reading problems. They noted that studies comparing binocular and monocular reading and those which calculate composite vision indices (including "scores" for binocular function) both indicate that binocular vision anomalies are related to reading. When looking at specific binocular problems, the authors found evidence for a correlation between reading disability and heterophoria and fusional vergence reserves, although one rigorous study disagreed with this. In particular, they deduced that exophoria and fixation disparity at near, and poor convergence are probably related to reading ability; and anisokonia, anisometropia, and stereopsis may be related; but they stressed that more research is needed. Simons and Grisham (1987) concluded that binocular anomalies are involved in some reading problems, although they criticised many studies for using unsatisfactory criteria to select their subjects. They stressed that it is better to look for combinations of binocular vision anomalies than for individual problems, and noted the important role of compensatory mechanisms; they gave the example of fusional vergence reserves as the compensatory mechanisms for heterophoria. The omission of Mohindra and Schieman's (1976) study weakened the section on fixation disparity, and Simons and Grisham (1987) mis-represented the work of Stein and colleagues (*see* Section 3.3).

Beauchamp and Kosmorsky (1987) pointed out that most psychological research suggests that dyslexia is related to deficits in language coding. They reviewed genetic and neurobiological aspects of dyslexia (*see* Section 1.5.3) and stated that the phrase "eye-hand (in)co-ordination" is "monumentally meaningless" since virtually the entire central nervous system lies between the eye and hand; it could be argued, however, that this phrase does have a meaning, reflecting general nervous system co-ordination. They stated that the significance of the work of Stein and Fowler (1985) and Pavlidis (1985) is unknown. Beauchamp and Kosmorsky (1987) also outlined a chiropractic theory that reading disability is caused by "ocular lock" resulting from damage to 2 cranial bones. They concluded that if visual perceptual problems do not underlie dyslexia then training to improve visual perception is doomed to failure. This paper made some interesting points, but did not represent a comprehensive or representative review of the literature.

Mousel (1989) briefly reviewed the ophthalmologist's role in dyslexia. He concluded that dyslexia was not caused by poor visual perception, but by language problems, in particular a decreased ability to use language to code other types of information. Unfortunately, the author only took into account a very small amount of the available evidence (hardly any of the studies investigating visual perception in dyslexic children were included). He did not seem to appreciate the heterogeneity of dyslexia, and did not address the issue of why, if dyslexic children have a generalised language problem, their spoken language is normal.

Miles and Miles (1990) gave a brief review of some research on eye movements and vergence dysfunction in dyslexia. They concluded that further evidence was required before the significance of these findings could be established.

2.3 Basic Refractive Parameters

2.3.1 Visual Acuity (V/A)

Few studies have found any correlation between V/A and reading disability. Some studies used Emsley's (1963) distinction between vision (unaided Snellen acuity) and V/A (optimal Snellen acuity with correction), whilst in many cases the terminology is unclear. Several studies omitted to give details of the viewing distance and lighting levels. It would seem most appropriate for dyslexia research to use reduced Snellen charts at the reading distance, with the refractive correction normally used for reading. This seemingly simple test is further complicated by crowding and the effect of adjacent contours (Pascal, 1991). This means that letter and line spacing have a measurable effect on V/A, as does the type of letter, luminance, and contrast (O'Leary, 1988). The Snellen test is, however, the method of assessing visual function that is most commonly used in schools.

Fendrick (1935) found that distance and near V/A were worse in his RD group than in his control group and linked this to the teaching technique that was used. This study only recorded V/A as worse than 20/20 or at least as good as 20/20, and did not clearly differentiate between corrected and uncorrected V/A; other aspects of this research are described in Section 2.4. Robinson and Huelsman (1953) found a connection between reading disability and poor V/A. However, this finding seems to have been based on a pilot study with non-standardised vision screeners.

Eames (1959) in his review of the ophthalmic findings of 3,500 children, half of whom had reading disabilities, found that:

> "There was little difference in the incidence or central tendency of V/A among reading failures and unselected school children but there was some correspondence between V/A and birth weight among the premature, in whom reading failure was more frequent than among children of normal birth weight."

This finding is interesting, but could be explained by confounding variables such as socio-economic group and educational opportunities. The author noted that many hyperopic children have normal visual acuities due to excessive accommodation, that may cause fatigue when reading.

Norn et al. (1969) compared 117 dyslexics with 117 controls. They found no difference in distance V/A between the 2 groups. This study, which suffers from several methodological flaws, is described in the section on refractive errors. Watts (1970) examined 180 children, 50 of whom had a reading age 6 to 24 months behind that predicted from their non-verbal IQ; these comprised the RD group. The mean age of all groups was within one month of 86 months. He inferred from his results, which did not reach significance, that distance V/A is more sensitive to subnormal vision than near V/A. However, this finding seems to be based on a comparison of the number of children below 6/6 and N5; this is inappropriate since N5 is equivalent to 6/10 (Rubin, 1988).

Anapolle (1971) noted that the results of V/A tests were often inconsistent in the learning disabled; this was attributed to cyclospasm or attentional problems; the limitations of his study are described in Section 2.4. Drasdo (1972) compared 23 reading retardates with 24 controls; these were matched for age (mean 10.5 years), socio-economic background, and non-verbal IQ. The diagnosis of reading retardates was made by Child Guidance Clinics and a Centre for Child Study. Four of the reading retardates had V/A of 6/6 or worse in the best eye; however, the groups were not significantly different.

Sherman (1973) reviewed the eye examination results of 50 children who were "diagnosed as having a learning disability by the referring source". The ages ranged from 6 to 13 years, and 39 of the children were boys. He found that 10% of the subjects had a V/A of less than 20/40 in one or both eyes. Unfortunately no controls were used and no normative data for the population was given. Bishop et al. (1979) examined 147 children, aged approximately 8 years 6 months. This sample was not selected according to reading ability, and comprised the consenting patients of this age at a rural general medical practice. The researchers found that mean IQ (WISC-R) and reading ability (Neale) were not significantly correlated with distance and near V/A. It is not clear whether they analysed their results in terms of distance and near V/A independently, or whether they combined the results.

Bedwell et al. (1980) examined 40 children with a mean age of 13.7 years. They used a standard Snellen chart at 6 m, and used the Schonell R4 Reading Test and the Schonell Dictation Test E for spelling to classify the children into good or poor readers; the latter group were 2 or more years retarded in reading. They found that the V/A was not significantly related to the reading difficulty (chi-squared test).

O'Grady (1984) studied 227 children, all aged 7 years, who received educational and visual testing whilst wearing any glasses that were normally used in class. Unfortunately, much of the eye examination data were categorised as normal, border-line, or suspect; and some of the criteria that were used appear to be inappropriate, e.g., near V/A that was N8 or better was considered normal. The optometrist was also asked to make an overall assessment of the visual status of each child as either normal, border-line, or "full examination recommended". He also sent a form to the children's teachers enquiring about "visual symptoms"; no significant relationships were found between the teachers' check-list and vision disorders. The educational testing comprised the Peabody Picture Vocabulary Test; reading accuracy, comprehension, and rate from the Edwards Diagnostic Reading Test, and a Basic Numeracy Test.

An analysis of variance was used where each analysis used the vision variables as a single independent variable; the last 4 of the education variables given above were used simultaneously as a dependent measure of educational performance; and the measure of general ability (Peabody Test) was used as the co-variate. A disadvantage of this method is that the literacy and numeracy skills were combined; hence, some specific reading disabilities are likely to have been masked. O'Grady (1984) found that 5 of his vision variables identified groups that demonstrated a difference in their mean educational performance and were significant at the 5% level; these included unaided binocular distance vision, distance binocular V/A; and the optometrists' recommendations based on the overall assessment of vision status. He concluded that "vision factors play a role in learning disability."

Aasved (1987), in a study that is described in Section 2.4, did not find a significant correlation between distance V/A and reading ability. Holland (1988) reviewed the records of 169 children seen in an optometric practice over a 6 month period. 22% of the children had reading difficulties which were acknowledged by the school. Although no figures for V/A were quoted, he stated that: "the vast majority of learning disabled children have acuities of 6/6 ".

Atkinson (1991) measured the crowding effect, which is the ratio of acuity for identification of a single letter compared with acuity for letter identification when it is surrounded by other letters or visual material. Some dyslexic children did seem to show a greater crowding effect than chronological or reading age-matched controls. This study suffered from methodological weaknesses, and is discussed further in Section 9.2.1.

The literature seems to suggest that distance V/A is not a strong correlate of RD. As already stated, near acuity would seem a more logical measurement for this type of problem.

2.3.2 The Contrast Sensitivity Function

The Snellen test is now 100 years old, and in recent years its limitations have become increasingly apparent; in particular, it only measures the resolving ability of the eye at high contrast. An alternative method of assessing the function of the eye is to measure the Contrast Sensitivity Function (CSF); the advantages of this were summarised by Drasdo (1988a):

> "The Snellen acuity relates to a level of resolution which the average observer rarely encounters in normal daily activity, whereas the CSF relates to low spatial frequencies and lower contrasts which are continually encountered."

Hyvarinen and Laurinen (1982) measured the contrast sensitivity of 20 dyslexic children. They said that the contrast sensitivity differences between good and poor readers were small, but suggested that contrast sensitivity measurements should be part of the clinical examination in children with RDs. It is difficult to establish the validity and significance of the authors' conclusions for the following reasons: few details of the way in which the subjects were selected or of their characteristics (e.g., age, sex, or psychometric data) were given; all of the subjects had reading difficulties, hence, there was no real control group; very few details of the eye examination and psychophysical testing were given; and few results were given.

Some other workers have evaluated disabled readers in terms of their CSF (e.g., Lovegrove et al., 1980).These studies are reviewed in Section 2.7.1.

2.3.3 Refractive Errors

Fendrick (1935) found, using a Keystone instrument, increased astigmatism in his RD group compared with the control group, and linked this to the teaching technique that was used; this study is described in Section 2.4. Farris (1936) outlined a large study that had found that hyperopia was associated with poor progress in reading, whilst myopia and myopic astigmatism were both associated with unusually good progress; unfortunately, too few details of this study were given to fully assess the significance of their findings.

Taylor (1937), in a study that is described in Section 2.4, found that the following conditions were present more often in "school failures", relative to "normal children": increased hypermetropia; decreased myopia; and an increased need for, yet decreased use of, a refractive correction. Park and Burri (1943), in a study described in Section 2.4, found refractive errors to be only slightly correlated with reading disability. They also made the interesting observation that poorly fitted spectacles correlated with low reading scores; unfortunately, few details were given and the refractive error was assessed in terms of "those needing glasses" (no criteria were given).

Eames (1948) compared the eye examination results of 1,000 "reading failures" with 500 ophthalmic patients and 150 unselected children; although all the subjects were aged between 9 and 11 years, no other details were given, no selection criteria for the RD children were given, and the groups were not matched for age or intelligence. In each group, the descriptive statistics for several optometric variables were contrasted, and were then statistically compared, taking a p-value of 0.10 as significant. The RD group were significantly more hypermetropic, had a lower IQ, and had a decreased speed of word recognition. The poor word recognition is not surprising considering the children's disability; the hypermetropia may to be related to the IQ and independent of the reading performance. This paper contained very few details of the methodology; the binocular vision results are discussed in Section 2.4.

Eames (1955) examined 57 children who were good readers and 64 poor readers. Within the group of poor readers, the hypermetropes read a median of 1.1 years, and the myopes 0.4 years, behind the emmetropes. In the group of good readers, the reading performance of the hypermetropic children was similar to that of the emmetropes, and the myopes read better than the others. The author concluded that refractive error had little effect on reading for good readers, but that hypermetropia had a detrimental effect on reading in those with a reading disability. This study suffered from several weaknesses: the selection criteria and definitions of hypermetropia and myopia were vague and unempirical; no psychometric data on intelligence were available; and no statistical analyses were used.

Eames (1959) found hypermetropia of one dioptre or more in 43% of "reading failures", compared with 13% of "normals". Astigmatism occurred in 2% more of his reading failures, but the incidence of myopia was similar in both groups. The speed of perception was measured with a tachistoscope; a refractive correction under 3 D tended to reduce the speed of object and word perception, whilst spectacles over 3 D increased these variables. Full data for these results were not given.

Young (1963) measured the refractive error of 117 children. Their intelligence was assessed with 2 tests, only one of which required adequate near vision. The results suggested that myopes demonstrate relatively higher intelligence on some tests owing to better near visual performance. He found no evidence for a "pure" relationship between refractive error and intelligence, although his results suggested that myopes were significantly better readers than hyperopes and were slightly better than emmetropes. Unfortunately, this paper lacked some details, such as the method of determining the refractive error and the age of the subjects.

Schubert and Walton (1968) investigated the effect of induced astigmatism on reading performance in normal readers. The subjects were 35 optometry students, aged 22-47 years, who were asked to read text that was blurred with a + 1.00 x 180 DC lens (this type of lens has 2 principal powers). 63% of the subjects reported that the text was blurred, 69% found the task tiring, and 69% reported headaches. The authors concluded that astigmatism is a major cause of asthenopia and that uncorrected astigmatism may result in a confused perception of letters and words. This study suffered from several weaknesses: no objective measures of the effect of the induced astigmatism were obtained; the authors did not point out that the type of astigmatism that was induced would result in a horizontal blur, that should have a maximal effect on reading; and they did not consider that a child may adapt to a permanent or slowly changing astigmatism in a different way to an experienced reader with "sudden onset astigmatism".

Norn et al. (1969) differentiated primary reading retardation (dyslexia), which they believed resulted from a hereditary lesion of the parieto-occipital lobe, from secondary reading difficulties. Their subjects were 117 dyslexic children (stated to have normal IQ) and 117 controls. They found that twice as many of the dyslexic children wore glasses, but that the type of refractive error and amount of anisometropia did not differ significantly between the 2 groups. It was concluded that visual defects are not causally related to dyslexia, but that they may worsen dyslexia. The authors stated that it was their practice to tentatively prescribe low plus spectacles for dyslexic hyperopes as an experimental correction. Norn et al. (1969) seemed to have a rather insular view of the aetiology of dyslexia, which did not relate to the current psychological literature. Their definition precluded visual anomalies from being a cause of dyslexia, an exclusion which they looked upon as a fact rather than as an assumption. They classified dyslexic children by their "reading quotient", which was calculated by dividing the child's reading age by the number of years he had been at school. The control group was not matched for IQ, and no statistical data was given.

Grosvenor (1970) cited Hirsch and Munroe who, in 1959, had found a direct correlation between intelligence and myopia and had put forward 4 possible explanations: (a) myopia is an overdevelopment of the eye that correlates with a cerebral overdevelopment in cases of high intelligence; (b) intelligence test results are influenced by the amount of reading that a child does; (c) more intelligent children read more and thus become more myopic; (d) myopes have better near V/A and hence do better in intelligence tests that require near vision. Grosvenor (1970) found that myopic children had higher mean scores than hypermetropes on both the Otis Self-Administered Test and the Ravens Progressive Matrices Test; both these tests required near vision, but the latter was a "coarse" visual task whilst the former involved reading. Myopes also occurred in significantly greater numbers in "high ability" classrooms than in "low ability" classrooms. The author concluded that myopia was associated with above-average academic performance, and he thought it likely that all Hirsch and Munroe's hypotheses were working together to produce this result. Grosvenor (1970) did not consider the effect of binocular vision parameters on his result and the refractive error was determined by retinoscopy carried out by optometry students, whose accuracy was not always checked.

Watts (1970), in a paper that is described in Section 2.4, found more hypermetropia in his RD group, this did not reach significance. Grosvenor (1971) reviewed the literature on factors associated with hypermetropia and noted that hypermetropes, when compared to myopes, tended to show lower IQs. He highlighted weaknesses in the literature on the relationship between refractive error and RD, and concluded that the evidence to date could not prove or disprove whether a direct relationship between hypermetropia and RD existed.

Drasdo (1972) found hypermetropia to be the most significant ophthalmic correlate of reading disability. Hypermetropia over +2.75 DS in the maximum ametropic meridian was present in 7 of his 23 reading retardates compared with none of the 24 controls ($p = 0.005$); the groups were matched for IQ and other variables. There was a bi-modal distribution of ametropia in the RD group, indicating that the hypermetropic retardates may constitute a different group from the rest; Drasdo (1972) proposed 3 explanations for this. Firstly, a non-causal explanation that there is a separate syndrome with, for example, an aetiology of paranatal complications such as jaundice or anoxia, (these are known to cause other forms of cerebral dysfunction which tend to be associated with hypermetropia). Secondly, a more obvious explanation of the second peak in the ametropic distribution is that hypermetropia becomes a very significant causal factor at a critical level. Thirdly, the results could be caused by an experimental artifact; e.g., a relaxation of accommodative tonus due to spectacle wear.

Sherman (1973) found 16% of his learning disabled group had myopia of greater than 0.75 D or hyperopia over 0.50 D. Due to the lack of controls or normative data, the significance of this finding is unclear. Dunlop (1975) found that only 24 out of 345 dyslexic children undergoing orthoptic treatment for unfixed ocular reference needed spectacles. Nevertheless, she felt that small degrees of astigmatism in the desired reference eye should be corrected. Dunlop (1979) reviewed her 7 years of experience with over 1,500 dyslexic patients, and stressed again that small refractive errors should be corrected, especially if "the greater error is in the desired reference eye". She did not specify what type of refractive error, although presumably low myopia is not significant.

Garber (1981) noted that American Navajo Indian children are known to have unusually high degrees of with-the-rule corneal astigmatism. He defined high astigmatism as greater than 2 DC by keratometry, and investigated the relationship between this and several other factors in 809 unselected Navajo children, aged 5-11 years. The incidence of high astigmatism was not significantly related to the results of a reading test (Stanford), but was significantly related to teachers' grading of their reading performance; this was scored as below average, average, good, or excellent. Unfortunately, some children only had their reading assessed by the reading test or by the teachers, and the author did not consider that some subjects could have had high corneal astigmatism that was compensated for by lenticular astigmatism; this would seem to be the most likely explanation for the finding that only 33% of those with high astigmatism demonstrated V/A worst than 20/30. The author did not suggest the simple hypothesis to explain his results that inbreeding had resulted in some children manifesting decreased intelligence and high corneal astigmatism; this is supported by the fact that the teachers' grading was more likely to be influenced by intelligence than the reading test result.

Hyvarinen and Laurinen (1982) carried out an eye examination on 40 dyslexic children and concluded that the prevalence of high refractive errors was much higher than that reported in children of the same age. This study had several weaknesses that were noted in Section 2.3.2. Fowler and Stein (1983) believed that anisometropia actually helps a child to learn to read since the eye with the better V/A for near becomes the dominant eye from the beginning, avoiding later dominance problems. O'Grady (1984) found the distance retinoscopy result was associated with lower academic performance, although the type of refractive error was not given (*see* Section 2.3.1).

Haddad et al. (1984) examined 73 subjects, aged 6-13 years, who were diagnosed by the referrer as having reading difficulties (a control group was not included). An extremely subjective method was used to assess reading performance, and they found that the reading difficulty was ameliorated by glasses for the 18 children who had refractive errors at near. Rather confusingly, the researchers went on to stress that dyslexia is not caused by ophthalmic problems. No details were given of diagnostic criteria for dyslexia, or even the definition of dyslexia that was used in the study.

Holland (1986), compared those children seen in an optometric practice with the symptom of reading disability (59 children) with those without (110 children). The refractive findings are summarised in Table 2.3.

group:	total sample	RD sub-group
myopia	33%	19%
low hypermetropia (uncorrected)	51%	62%
high hypermetropia	16%	19%

Table 2.3 Summary of the refractive results from Holland's (1986) study. The incidence of various refractive errors in the RD group was compared with that in the combined RD and non-RD groups ("total sample").

The parameters by which the refractive errors were defined are not given, although a low hypermetropic prescription seemed to refer to one which the optometrist decided not to correct. If this is the case, the results could have been confounded by a tendency to correct lower refractive errors in RD children. The effect of the prime symptom was another confounding variable and the incidence and effect of astigmatism was not considered.

Rosner and Rosner (1987a) presented data on 757 children, aged 6-12 years, who were seen at a university optometry clinic over a period of 14 weeks. The children were classified as having learning difficulties (261) or not (496) solely on the basis of comments by schools or parents; hence, the "suspect" group could not be described as dyslexic, and may not even be learning disabled. The authors found an increased incidence of hyperopia among the group with learning difficulties, but this was not subjected to statistical analysis. Astigmatism was (unusually) defined as where the cylindrical component of the prescription amounted to 50% or more of the spherical component; this was similar in both groups. It appears that the 2 main presenting symptoms were either learning difficulties or myopia; this invalidates the significance of findings on the relative incidence of refractive anomalies in the 2 groups.

Walton et al. (1987) addressed 3 questions concerning the effects of induced hyperopia: the effect on reading ability; the effect on symptoms; and the level of hyperopia that required referral to an eye care practitioner. Their subjects, who were 42 students aged 22-31 years, were assigned to 3 groups who either wore a pair of -1.00, -1.50, or -2.00 DS lenses. As the amount of induced hyperopia increased, the number of errors when reading and the speed of reading also increased; the latter finding was attributed to the subjects reading quicker to finish an uncomfortable task. Walton et al. (1987) concluded that, to optimise reading performance, hyperopia should be corrected if it was greater than 1.50 D, although to correct symptoms it should be corrected when in excess of 1.00 D. They also noted that the -2.00 DS lenses had more effect when there was a large AC/A ratio. It is not clear whether the centration distance of the trial lenses was controlled; hence, an induced prismatic effect may have confounded the results. The extent of the authors' statistical analysis was unclear. The authors attempted to correct their data for a practice effect because the no-intervention condition always preceded the intervention; a better method would have been to test half the subjects with the intervention first, hence eliminating this confounding variable. Further, the effect of immediately induced hyperopia in adults should not be equated to the effect of slowly developing hyperopia in children.

Adler and Grant (1988) studied the first year intake of a large secondary school. They used several tests to classify the children's reading age as: normal (53 children), 1-2 years retarded (14 children), and 2 or more years retarded (19 children). The percentage of hypermetropes (over +1.50 D) in each group was 4,7 and 0 respectively, and the percentage of myopes was 15, 14, and 10.5 respectively. These data do not suggest a correlation between these refractive errors and reading ability.

To summarise, there does not appear to be a high correlation of refractive error with reading disability, although some studies have found an increased incidence of hypermetropia in the reading disabled. One reason for the equivocal results and lack of a firm conclusion is the poor scientific methodology in many of the studies. The evidence suggests that refractive error is inversely correlated with IQ; hence, studies that aim to investigate the relationship between refractive error and reading performance must control for IQ.

2.4 Binocular Vision and Accommodation

Eames (1934) measured vergence reserves in a stereoscope using 3 different type sizes. His subjects were 88 RD and 52 control children; no details were given of the selection criteria for the subjects, or of their reading performance, intelligence, or age. Vergence reserves were quantified by the unusual method of measuring the vergence amplitude from the divergent recovery position to the convergent break point. The vergence amplitude reduced with decreasing print size in all groups, and was lower in the RD group for all print sizes. No statistical analyses were used in this study.

Fendrick (1935) studied 64 poor readers and 64 controls who were matched for age, number of years schooling, and intelligence; the mean age was 8.5 years and the RD group were at least half a grade behind in reading, with a mean of 2 years behind. All children were tested for V/A at distance and near; sighting dominance; dissociated heterophoria (Maddox Rod) at distance and near; and, on the Keystone instrument, V/A, fusion, stereopsis, heterophoria, and astigmatism. Fifty children from each group were selected for an optometric examination (it was not stated how these children were selected, and some details of the examination were lacking), and the main groups were also given several tests of visual perception, including visual search tasks. The Maddox Rod and Keystone results were similar in the 2 groups, but the optometric examinations revealed increased near heterophoria in the RD group. The RD group also performed significantly worse at the visual perceptual tests, but these results were not related to the optometric results. It was concluded that visual characteristics in RD need attention, and that the teaching method should take heed of the visual and auditory skills; it was suggested that all RD children with a sensory problem can be cured.

Farris (1936) outlined a large study that had found that strabismus was associated with poor progress in reading, and stressed the inadequacy of school screening tests based on the measurement of V/A. Unfortunately, too few details of this study were given to fully assess the significance of the findings.

Clark (1935) studied 11 university "freshmen" with an exophoria between 12 and 16 Δ and 11 controls, from the same sample, who had an exophoria of 0-2 Δ; the groups were matched for sex, reading comprehension, and linguistic ability. He measured their eye movements, by photography, whilst reading 2 paragraphs, and tested them for comprehension; a test of ocular dominance was also used, and this is discussed in Section 3.1.2.1. The groups did not differ significantly in terms of the number of fixations and regressions, although the average size of the divergence movements at the beginning of each line was 9.1' larger in the experimental group; this was said to be "probably significant". The duration of the divergence movements was not significantly different between the 2 groups. Clark (1935) concluded that the divergence movements probably caused enough excessive reading fatigue to be "of considerable importance from the point of view of remedial reading". This conclusion, in a study that used relatively short reading passages, must be speculative; and it was not stated whether the divergence movements were associated with rapid or slow compensatory convergence movements.

Taylor (1937) compared 100 children who were generally underachieving at school (described as "failures") with 387 "normal" children; no psychometric details were given and it is not clear whether the groups were matched in any way. Results obtained with the Keystone instrument suggested relatively increased suppression and near heterophoria, and reduced stereopsis in the experimental group. Base out distance fusional reserves were significantly reduced and base in reserves were slightly reduced in the experimental group (few details were given of the test procedure) relative to the controls. Other aspects of this study are described in Sections 2.3.3 and 2.5.2.

Dearborn and Anderson (1938) described the principal effects of aniseikonia as decreased stereopsis and fusional difficulties resulting in asthenopia; they hypothesised that it could interfere with reading either through ocular or general fatigue, or by interfering with the peripheral perception of the line of print, hence inhibiting the proper spacing of fixation pauses. They described the ophthalmo-eikonometer, which measures aniseikonia, and their study of 100 RD subjects of all ages and 100 age matched controls. Aniseikonia of more than 1% was present in 51% of the RD subjects, compared with 23% of the controls ($p < 0.001$); the range of aniseikonia was 1-7% in the RD group and 1-2.75% in the control group. The authors also found that reading disability was more directly related to aniseikonia at the near point than at distance ($p < 0.001$). They concluded that, whilst it was difficult to estimate how important aniseikonia was in RD, they felt it was a factor in approximately 50% of extreme cases. They also stated that the eye defects that had the greatest effect on reading performance were those which, like aniseikonia, impaired fusion.

Dearborn and Anderson (1938) did not use the same reading and IQ tests on all subjects. The difference between the subject's IQ and reading age was given as 2 years 20 months ± 1 year 4 months; hence some of the subjects were only slightly retarded in reading. The selection of the controls was also suspect, since these seem to have visited the clinic with the symptom of reading difficulty, but were found on testing to have normal reading. The authors stated that the 2 groups were not matched for IQ because this is not related to aniseikonia; however, it seems likely that the subjects' ability to make judgements in the Ophthalmo-eikonometer would have been related to IQ. They also argued that, although their clinic had a reputation for investigating aniseikonia, this did not mean that patients consulting them had a greater likelihood of suffering from this condition since a person is unable to tell whether or not they have aniseikonia. Whilst this much is true, patients with asthenopia would probably have been more likely to visit the clinic than those without, and hence the sample described in this study does not represent the general population.

Knehr (1941) investigated the hypothesis that reading efficiency was increased by dispensing with the need for binocular fusion by occluding one eye. Reading efficiency was assessed by eye movement analysis, and this study is therefore discussed in Section 2.5.2. Berens, in a discussion appended to Orton (1943), reported the observation that aniso-accommodation and rapid fatigue of accommodation interfered more with the function of reading than low degrees of heterophoria and ametropia.

Park and Burri (1943) referred to their previous work, which had shown reading skills to be inversely correlated with eye abnormalities, and reported a study that in many respects was far ahead of its time. For example, they made the simple, but often ignored, point that:

> "It is obvious that there are many factors in reading difficulty, and any one will affect or change the total complex function of reading dependent upon the ability of the individual to adjust himself to any abnormality which presents itself."

This study evaluated 220 unselected children, aged 6-13 years, who were given an eye examination in which each defect was scored as 1 point; these were summed to give a "total eye score". The authors obtained equivalent ages from reading and IQ tests and demonstrated the importance of controlling for IQ. The authors showed that low reading scores that were associated with a high IQ correlated more significantly with eye defects than poor reading that was associated with a low IQ; Rutter (1978) supported the existence of a distinct group of RD individuals with a high IQ. Park and Burri (1943) found that exophoria and fusional reserves (particularly the prism to recovery) were significantly correlated with reading ability. The relationship between reading ability and eye defects did not vary in the different age groups. The details of the eye examination procedure in this paper were rather vague and the method of scoring visual defects did not take account of the severity of the defects. The subjects' reading age and IQ were obtained from school records and it appears that these were only accurate to the nearest year, although this information was not clear in the paper.

Eames (1948), in a study that was described in Section 2.3.3, found a statistically significant increased incidence of near exophoria in children with a RD. This study "scored" both exophoria and esophoria as either greater or less than 6 Δ; since a low degree of exophoria at near is physiological (Pickwell, 1989, p. 57) this would have resulted in an unrealistically high incidence of exophoria. Although Robinson and Huelsman (1953) reported a connection between poor stereopsis and RD, most of the instrumentation used in this study was built by the authors and does not appear to have been standardised.

Eames (1959) found that strabismus occurred almost twice as often in his 1,750 RD patients as in the same number of controls. No figures or statistical analysis were given, but he stated that the overall incidence was low, and that convergent strabismus was the most common type among the reading failures. He also noted more high exophoria in the RD group, and said that hyperphoria was rare in both groups but slightly more common in the RD subjects.

Benton et al. (1965) carried out eye examinations on 250 "dyslexics" (no selection criteria were given) and found convergence insufficiency (defined as an inability to hold convergence on a point 6 cm away for 5 seconds) in 29%, in comparison to the quoted incidence in the general population of 10% (no reference for this was given). They related this finding to crossed, mixed, or incomplete dominance in their sample (*see* Section 3.1.2.1) and the subjects were said to respond well to treatment. No control group was included, it is not clear whether the subjects were selected in any way, and no quantitative analysis of reading performance before or after treatment was given.

Dunlap (1965) described a small study, of 30 RD children, that lacked a control group or placebo treatment, yet noted that "our results are so uniformly good as to invite disbelief." Dunlap (1966), in an essentially identical paper, stated that a comitant heterotropia could not cause a reading problem, but that the effort to control a muscle imbalance can result in inefficient reading. He believed that prolonged periods of Marlowe occlusion could lead to the detection of small vertical heterophorias which should, in dyslexia, be corrected surgically (c.f., orthoptically). Solomons (1978, p. 215) pointed out that Marlowe occlusion, which is the practice of permanently occluding an eye for as long as 14 days and then re-measuring the heterophoria, may not measure the "true" heterophoria and can actually cause a strabismus; hence, advocating surgical treatment on the basis of "prolonged" Marlowe occlusion would seem highly unorthodox. Dunlap (1966) presented data for 35 RD patients (poor selection criteria were used) who had been treated in this way; there was no control group and he admitted that the placebo effect may have been a factor. It is surprising that Dunlap (1966) did not seem to take account of the vergence reserves opposing the heterophoria; although it is interesting to note that he also often found convergence insufficiency in cases of RD.

Shearer (1966) studied 220 children, who were selected by their teachers as being at least 1 year behind in their reading, from an original sample of 2,177 elementary school children. Screening tests, on a Keystone instrument, revealed that 54% of the RD group had "sight problems" (not defined) and further analysis (few details were given) revealed increased convergence insufficiency and exophoria at near compared with "the average child". The absence of a control group, data, or test details makes these results difficult to interpret.

Bettman et al. (1967) examined 47 dyslexic children (diagnosed by a Paediatric Child Study Unit) and 58 age-matched control children, whose reading was "above average". The following parameters were significantly correlated with dyslexia: family history of dyslexia, pregnancy complications, sex (more males), minimal cerebral dysfunction (by neurological testing), foveal suppression (4Δ test), jerky eye movements, and abnormal retinal rivalry. The following were not correlated with dyslexia: early developmental progress (e.g., first sentences and walking), fusional amplitudes and accommodation, laterality (measured by several methods), and mixed dominance. This was a fairly comprehensive and rigorous study, although the controls are not matched for IQ.

Benton et al. (1968) described the procedure for RD children in their ophthalmology practice. They believed that from the results of the eye examination, dominance testing, and auditory or motor tests the children could be classified as having a visuo-motor, visuo-auditory, or visuo-optic defect. The characteristics of these defects were described and visuo-optic children were said to have atypical dominance, refractive errors, and binocular vision problems; 20% had convergence insufficiency. The authors presented very little data, their groups were poorly defined, and no statistical analysis was given. Mayou (1962) reported the anecdotal observation that children who were slow readers often exhibited esophoria at distance combined with poor convergence at near.

Birnbaum and Birnbaum (1968) reasoned that visual confusion whilst reading could result from poor binocular co-ordination, particularly if this was intermittent and was not severe enough to cause suppression. Their subjects were 47 children, 15 of whom were good readers and 32 of whom were poor readers (few details of the subjects or selection criteria were given, and it is not clear whether they were matched in any way). The authors compared the monocular and binocular performance at reading passages; the results suggested that binocular relative to monocular function was best in normal readers, poorer in bad readers, but worst of all in good readers. The results were severely confounded by a practice effect, it seems that a blind protocol was not used, and the role of ocular suppression in compensating for a binocular vision problem was not considered.

Silbiger and Woolf (1968) investigated the relationship between fixation disparity and reading achievement at the college level. The subjects were 18 year old university students, 25 of whom had scored in the top third of results at a speed of comprehension test and 38 of whom had scored in the bottom third. The lateral phoria was assessed, and the fixation disparity was measured for three conditions: with 5 Δ base in each eye, 5Δ base out each eye, and no prism. Reading ability was significantly inversely correlated with over-convergence on the fixation disparity test, and with the presence of a fixation disparity for the no prism condition (the significance of a correlation, however, is a poor measure of the strength of an effect). The authors only found a slight tendency for poor reading to be correlated with under-convergence on the fixation disparity test; all other tests were not significant. They concluded that RD was correlated with esophoria, and that fixation disparity tests, where a fusional lock was present, were a more appropriate test for investigating reading anomalies than conventional phorometry. This paper suffered from some weaknesses: some of the terminology was unconventional rendering the results difficult to interpret; the subject's IQs were not measured; the vision tests, which were carried out on a screener, did not include a refraction; "minimal movement" on the fixation disparity test was not scored; and the authors did not state the type of fixation disparities that were present for the no prism condition. Their finding of over-convergence in RD subjects concurred with their previous work, but not with the bulk of subsequent research.

Norn et al. (1969) examined 117 dyslexic (stated to have normal IQs) and 117 control children. They found that strabismus occurred more frequently in the control group and heterophoria slightly more frequently in the dyslexic group. This study has several methodological flaws, which were described in Section 2.3.3.

Watts (1970) assessed the distance and near muscle balance, motility, near point of convergence and stereopsis (Wirt stereotest) in his group of 180 seven-year-old children, some of whom had a slight RD. He found no statistically significant correlation between any of these parameters and reading retardation (poorer stereopsis in the reading retardates nearly reached significance).

Anapolle (1971) examined 482 people, aged 2 to 48 years; 80% were male and it was implied that they had learning disabilities. She found that many of her subjects had unusually high exophoria, low fusion amplitude, and poor stereopsis. The importance of these findings cannot be determined because: no subject selection criteria or psychometric data were quoted; very few details of the test procedures were given; virtually no useful optometric data were quoted; no control group was included; and it was not pointed out that a small exophoria was physiological. Drasdo (1972), in a study that was described in Section 2.3.3, found that 4 out of 23 reading retardates had a manifest strabismus (at distance or near) compared with none of his 24 controls; this did not reach significance.

Hammerberg and Norn (1972) assessed accommodation and its relationship with vision training and convergence in 78 children at a special school for dyslexic individuals. Twenty-one (27%) were found to have accommodative insufficiency (differentiated from fatigue); orthoptic investigation showed that 13 of these had decreased convergence, which was successfully treated with exercises. The authors concluded that these children had defective dissociation of accommodation and convergence, but believed that this defect was not associated with dyslexia. This study was flawed by the following methodological problems: no subject details were given; the selection criteria were inadequate; no reading or IQ tests were used; details of treatment or its effect on reading were not given; and no justification was given for the conclusions.

Ludlam et al. (1973) gave a case report of a 14 year old boy with poor convergence, poor accommodation, and pseudo-myopia. Vision training (for 3 months) and a + 1.25 DS prescription resulted in a dramatic improvement in reading performance, which was sustained for at least 1 year.

Sherman (1973) examined 50 learning disabled children and found that: 3 had alternating exotropia; 1 had alternating esotropia; 46 had problems with binocular fusion; and 48 had ocular-motor efficiency defects (pursuit and saccadic fixation ability). There were no controls, statistical analyses, or consistent criteria for the diagnosis of learning disability; and some details of the optometric methods were lacking.

Dunlop et al. (1973) found reduced convergence and stereopsis in a RD population. This study incorporated a new test of ocular dominance that became the core of a large body of subsequent research, which is described in Section 3.3. It should be noted that binocular dysfunction was assigned an increasingly important role by the researchers who used this test in later years (e.g., Riddell et al., 1988b; Stein, 1991a); for continuity, however, the studies that constituted this line of research will all be reviewed in Section 3.3.

Brod and Hamilton (1973) used induced aniseikonia to investigate the effect of a disturbance of binocular vision on reading. Their subjects were 162 children, aged 10 years, comprising equal numbers of good, poor, and average readers. They read 3 passages, of equivalent difficulty, with the intervention of a 1.25 x 90 aniseikonic lens in front of the right eye, the left eye, and without the intervention. The researchers found a significantly increased number of errors with the intervention, and concluded that a disturbance in binocular function impaired reading performance. These authors made several unsubstantiated claims; e.g., that a disturbance of binocular vision had a worse effect on reading than monocular occlusion. It is unclear whether they used a blind protocol, and the subject's reading ability was rated purely on the basis of teachers impressions; however, this information may have been redundant since they did not seem to compare the different reading level groups. The authors' results also showed an important trend that they did not comment upon; this relates to ocular dominance and is described in Section 3.2.7.

Marcus (1974) measured the fusional reserves, near point of convergence, accommodative facility, and pursuit and saccadic eye movements in 60 learning disabled children. He used a 5 point scoring system, which was said to be related to clinical norms, to obtain a binocular efficiency score; it is not clear why pursuit and saccadic eye movements were included. The author found that his group "scored less than the expectant" on most of his visual measures and suggested that learning disabled children have an inept visual system. He erroneously described these signs as symptoms and stated that they revealed "a syndrome of inefficiencies in visual processing." The eye movements seem to have been assessed by subjective observation, no psychometric details or selection criteria were given, and there was no control group.

Beaver (1975) measured the reading eye movements of 14 normal subjects when the following prisms were placed in front of the right eye: 0 / 2 / 4 / 6 Δ base out, and 1 / 2 / 3 Δ base up. The interventions resulted in an increased number of regressions, number of fixations, and time taken to read the passage. It is surprising that only type 2 regressions (those occurring within a line) were increased: type 1 regressions (those at the beginning of a line) were unaffected. No details were given of the subjects' age or refractive error, nor of the time lag from when the prisms were inserted to when the passage was read; this may relate to prism adaptation. The author concluded that heterophoria, particularly in poor readers, should be treated; this use of the results to draw inferences on the effect of heterophoria in a developing reader may not be justified.

Mohindra and Scheiman (1976) criticised the relevance of measuring the dissociated phoria and fusional amplitudes, mainly because these measurements produced an artificial situation. They preferred fixation disparity techniques where:

> "in the presence of binocular vision and fusion, the pattern of innervations being sent to the extrinsic ocular muscles is different from that when the eyes are dissociated."

Their subjects were 61 normal students and 53 learning disabled students, all aged 9-14 years and with average or above average IQ. The learning disabled group were diagnosed on the basis of a battery of tests, although the degree of learning disability was not given. The children were tested with the Mallett Fixation Disparity Test for near (with near correction if prescribed) and a "blind" protocol was used throughout. The researchers used the unusual technique of asking the children to draw the appearance of the targets and diagnosed a fixation disparity from the drawings; this method could result in errors and one of the "pass" drawings in the paper could be interpreted as representing a fixation disparity. The incidence of fixation disparity was not found to be significantly different for the two groups.

Chernick (1978) briefly described the eye examination results for 80 RD children. He found an increased incidence of defects of: fusion, stereopsis, convergence, accommodative facility, and oculomotor skills; he used these results to argue for better school screening tests by optometrists. The only selection criterion applied in this study was that the subjects were 2 years or more below grade level in reading; the grade level does not necessarily relate to the chronological age, and no IQ values were given. This study suffered from several other weaknesses: there was no control group and no normative data; most of the results were defined according to arbitrary pass/fail criteria; and the methods of oculomotor testing were extremely subjective.

Létourneau et al. (1979) measured the near point of convergence (NPC) in 735 children, aged 7-14 years, and found that 8.3% demonstrated "poor convergence" (more remote than 10 cm). From one school, he selected 25 children with poor convergence and 251 who had "normal" convergence and found that the groups did not differ in "reading-spelling" performance; the statistics quoted for this were unclear but seem to indicate a border-line significance, although the direction of the relationship was also unclear. The correlation between "IQ" and NPC, when greater than 10 cm, was not significant; no data or test details for the IQ were given, and no reason was given for using correlational statistics on 25 subjects instead of comparative statistics on the whole sample. It seems apparent from the author's literature review that most studies which chose a pass/fail criterion for the NPC of 5 cm found a significant relationship with academic performance, whilst those that chose 10 cm as the criterion did not; hence the criterion in his study may be inappropriate. Indeed, the preferred method might be to use the NPC data as a continuous variable. Other weaknesses of this study included the use of a target that is a poor stimulus to accommodation; taking measurements from the bridge of the nose instead of the corneal plane; and a failure to consider the potential confounding variable of foveal suppression.

Hoffman (1980) reported eye examination results from 87 male and 20 female learning disabled children (no consistent diagnostic criteria were used) who were aged between 5 and 14 years, with a mean age of 8 years. The results were compared with normal levels of performance (no supporting references for these were given, and many seem to be arbitrarily chosen) and with the results for 25 children who had been referred for eye examinations for reasons other than learning problems; the psychometric profile of this group was also unknown and they should not be considered as visually "normal". Owing to these methodological weaknesses, the findings of "mechanical visual problems", particularly poor accommodation and binocular co-ordination, and visual perceptual motor difficulties (*see* Section 2.7) in children with learning disabilities are difficult to interpret.

Bedwell et al. (1980) stressed the importance of assessing dynamic (compared with conventional static) binocular vision in dyslexia. They assessed 40 children, aged 13 years, 25 of whom were 2 or more years behind in reading and 15 of whom were reading at their age level or above. The Titmus Vision Screener was used to measure the heterophoria, suppression, and stereopsis; only the stereopsis was significantly related to reading ability ($p < 0.05$). The positive and negative fusional reserves, measured with vectographs, were not related to reading performance although the poor readers were more likely to have experienced diplopia when reading ($p < 0.5$). Independent experienced observers examined video recordings of the head and eyes during reading; this was carried out without sound, according to a blind protocol, and the subjects' heads were not restrained. The results of the analyses of the inter-group differences are given in Table 2.4.

variable	inter-rater reliability	p <
instability in co-ordinating the eyes on looking from left to right	0.748	0.01
indecision as to controlling eye while reading	0.655	0.05
unequal eye movements while reading	0.710	0.01
both eyes tending to diverge while reading	0.795	0.05
one eye tending to diverge and then over-converge while reading	0.765	0.05
compensatory head movements while reading	0.853	0.001
facial muscular stress while reading	0.751	0.06

Table 2.4 Summary of Bedwell et al.'s (1980) analyses of inter-group differences in terms of dynamic visual performance whilst reading. Further details are given in the text.

Despite the randomised blind technique, it seems likely that the observers knew from the subjects' speed and general relaxation whether they were from the RD group. It should also be noted that the variables in Table 2.4 could be the effect rather than the cause of a reading problem. Bedwell et al. (1980) concluded:

> "Manifestations of binocular image confusion are likely to be produced that may be associated with such situations as errors in reading through visual mis-cueing and difficulty in spelling because of poor visual sequential memory.
> In the context of reading difficulty it is likely that the children who have never developed adequate ocular control will have difficulty in learning to read and to spell, especially if taught by near visual methods. Others, who have learnt the elements of reading when young, especially if aided by phonics and some distance viewing of words, may later experience difficulty and possibly regression, if binocular control is inadequate to prevent confused visual input as the speed of work and visual fatigue increases."

Poynter et al. (1982) examined 74 children, aged between 9 and 11 years. They assessed 4 oculomotor functions; 3 of these were related to eye movements (*see* Section 2.5) and the fourth was the lag of accommodation. This was measured during prose and digit reading by heterodynamic or MEM (monocular estimate method) retinoscopy. This involved near fixation retinoscopy whilst rapidly interposing plus lenses monocularly in front of each eye until neutrality is achieved. The authors found that, regardless of verbal intelligence, reading disability was related to lag of accommodation; these findings were "questionably significant" and accounted for 6-8% of the variance in reading ability.

Hyvarinen and Laurinen (1982) carried out an eye examination on 40 RD children and concluded that the prevalence of abnormal binocular functions was unusually high. This study had several weaknesses that were noted in Section 2.3.2. Skagseth (1982) briefly described some preliminary findings from a large study investigating visual problems in dyslexia. He stated that ophthalmic and orthoptic abnormalities were rare, although this was not supported by data or statistical analyses.

Irlen (1983) claimed to have discovered a condition that could not be detected or treated by "conventional ophthalmological means" and required specially prescribed tinted lenses. This condition, which may in some cases be a manifestation of a binocular vision problem, is discussed in Chapter 4.

Haddad et al. (1984) examined 73 subjects, aged 6-13 years, who were diagnosed by the referrer (mainly teachers or speech therapists) as having reading difficulties (no control group was included). The subjects' reading was evaluated by a modified Monroe method; this seems to be extremely subjective and a blind protocol does not appear to have been used. Thirty-seven of the children were found to have poor (quantitative data were not given) fusional amplitudes (both convergent and divergent); in all of these orthoptic exercises improved their attention span as measured by the Monroe method. The researchers stressed that dyslexia was not caused by ophthalmic problems, although they believed that poor fusion would cause fatigue, focussing difficulty, and an unstable perception of printed text. No statistical analysis or details of diagnostic criteria for dyslexia were given.

O'Grady (1984) found fixation disparity to be associated with lower academic performance (*see* Section 2.3.1). The criteria that were used for many of the binocular vision tests in this study were inappropriate; e.g., cover test results were scored as ortho-/exo-/eso-phoria/tropia and any near point of convergence more proximal than 13 cm was considered normal.

Atzmon (1985) investigated 150 cases who were randomly selected from 800 children (aged 4 years or more) and adults with reading or learning difficulties; no precise diagnostic criteria were given. He measured convergence, accommodation, absolute and relative vergences, and stereopsis. In most subjects the absolute vergences were within normal limits, but relative vergences were lower than the quoted norms. Accommodation was also poor in some cases, although stereopsis was normal (Titmus test). This study did not employ any controls or statistical analysis, the binocular vision problems were not related to the refractive error, and details of the accommodative findings were sparse.

Franklin (1985, unpublished) suggested that reading matter, with its uniformity and paucity of depth cues, could promote the breakdown of binocular vision. He described eye movement records of dyslexic case studies demonstrating variable heterophoria and heterotropia during reading, and suggested that this could result in retinal rivalry, which in turn could cause false stereopsis and sequencing and a generally confusing binocular percept. He believed that Stein and Fowler's (1985) occlusion therapy (*see* Section 3.3) had a beneficial effect in dyslexia because it removed the random element of this confusing binocular percept. He used the branch of mathematics called Catastrophe Theory to explain RD in terms of the combined effect of several inconsistent factors, including unstable binocular vision; improvement in any one of these factors could significantly reduce the RD.

Moseley and Lane (1986) described their research over a 20 year period and criticised tests that were carried out during short periods of static viewing. They thought that binocular dysfunction could cause RD through asthenopia, focussing problems, or image confusion; and noted that a difficulty in maintaining fusion may be more of a problem than the absence of fusion. The authors then described their research studies, all of which were based on normal school populations. In their 1967 Hackney study they examined 2 groups of children, aged 8-9 years, both of whom had at least average receptive vocabulary. The experimental group comprised 52 boys and 8 girls with specific spelling problems and the controls were 37 boys and 32 girls of average spelling performance. The reading performance was only obtained for the experimental group, but measurements of the near phoria (Maddox Rod) and fusional convergence (using a stereoscope) were obtained for both groups. Within the experimental group, convergence insufficiency (no criteria were given) was significantly associated with a slow rate of reading and those with both esophoria and convergence excess (no criteria were given) had significantly worse reading and spelling attainment than the rest of the group. It is unfortunate that this study reduced the data, which was measured as continuous variables, to discreet binary ordinates on the basis of seemingly arbitrary cut-off criteria.

Moseley and Lane's (1986) Barnett study in 1977 investigated 39 boys and 17 girls (aged 9 to 10 years) who had been previously identified as among the 12% most backward readers in the borough. They were questioned about symptoms of asthenopia, blurring, and doubling. The 30% who complained of 2 or more symptoms (another arbitrary criteria) had made less reading progress than the others, although this was not significant. This study was weakened by the lack of a control group and it was assumed that the children would recognise their symptoms, which may have been present from a very early age.

In their 1978 Newcastle study the authors investigated 17 boys and 23 girls (aged 7 to 8 years) with a wide range of reading attainments. The listening comprehension was assessed and they carried out 2 visual search tasks, both of which involved a significant motor component (ringing or placing Xs with a pencil). The first task was performed with the preferred eye (no details were given) as well as binocularly. The second task was carried out through a stereoscope in such a way that an esophoria should have caused an altered response; this was not confirmed by conventional measurement of the heterophoria, and exophorias were not investigated. There were non-significant tendencies for the 6 children with superior monocular performance and for those with esophoria to have lower reading and spelling scores. However, those in the "esophoric group" did have significantly worse reading scores relative to their listening comprehension.

Moseley and Lane's (1986) North Tyneside study in 1983 compared 27 good with 23 poor readers; the groups were both aged 8 years, and it appears that they were approximately matched for sex, but not for IQ. The Bausch and Lomb Orthorater was used to measure near acuity and lateral muscle imbalance, and the range of fusional convergence was measured with a stereoscope. A visual search task (again with significant motor components) and a modified version of Grant's Visual Recall Test were carried out monocularly and binocularly. Both binocular and left eye (but not right eye) acuity were significantly inferior in the poor readers, and those children with differences between right and left acuity performed better monocularly than binocularly on the scanning test. None of the other results reached significance, although the 4 children who had a narrow range of fusional convergence (no details were given) were said to perform better monocularly (no details), and 3 of these were poor readers. Other weaknesses of this study were that the data were not analysed as continuous variables; only esophoria, not exophoria, was considered; and it was incorrectly assumed that unequal monocular acuities was synonymous with anisometropia.

Moseley and Lane (1986) concluded that binocular inefficiency may result in minor acuity problems and that these occurred more often in the reading disabled. They felt that children with reading problems often reported anomalies of vision and asthenopia, and suggested that binocular inefficiency at the near point should be routinely investigated in children. They advocated comparing binocular with monocular performance at a reading-related task, but noted that binocular inefficiency may only become operative in concentrated near tasks and clear-cut cases of superior monocular performance are probably rare. Further investigation of the range of fusion was suggested, as were paradigms that considered reading in relation to listening comprehension. They felt that although esophoria and convergence insufficiency played a causal role in reading or writing problems, it is not known whether this adverse effect is through asthenopia or a visual effect. The assumption of a causal relationship may account for some of the weaknesses in their experimental designs.

Holland (1986), in a study that was described in Section 2.3.3, compared the results of several binocular vision tests for his RD group to those of his total patient base. Twenty-one percent of the RD group had squints, 30% had decompensated heterophorias, and 53% had poor convergence compared with 11%, 18%, and 27% respectively of the control group.

Rosner and Rosner (1987a) presented data from 757 children, aged 6-12 years, who had been examined at a university optometry clinic over a period of 14 weeks; unfortunately, the children were classified as having learning difficulties (261) or not (496) solely on the basis of comments by teachers or parents. The researchers found that vergence/accommodative infacility and strabismus were not significantly correlated with learning difficulties. Further analysis of these data by the present author reveals that the incidence of myopia in their non-LD group was 54% compared with 19% in the LD group; this is likely to have confounded their results and may invalidate the conclusions.

Holland (1987) stressed the importance of dynamic vision compared to static vision. He believed, unlike Bedwell et al. (1980), that dynamic vision was often associated with easily measurable static visual anomalies, such as the magnitude of the phoria, quality of recovery, and convergence.

Fricker (1987-1988, unpublished), in a study that is described in Section 4.2.2, found impaired stereopsis in 75% of RD children; 80% of these improved with the use of tinted lenses. This study suffers from several methodological weaknesses.

Aasved (1987) screened 3,000 school children in the first grade; no age details were given, but they were probably aged between 6 and 7 years. He found that strabismus, prism fusion, heterophoria, suppression, and stereopsis were unrelated to reading ability; these results are difficult to interpret because no details were given of the tests that were used. From this sample, he identified 259 dyslexic children (no details of selection criteria or psychometric data were given) who were classified into the following "dyslexia types": auditory, audiovisual, visual dyslexia, and others; details of the diagnostic criteria for these groups were not given. An eye examination failed to find significant differences between the groups in terms of: heterophoria, strabismus, prism fusion, near point of convergence, accommodation, stereopsis, and suppression. The few details of test procedures that were included showed that the convergence and accommodation pass criteria were unrealistically easy; the absence of refractive data further detracts from any useful interpretation of the tests of binocular function. Other aspects of this study are described in Sections 2.3.1 and 3.3; the author concluded from his experimental data and (limited) literature review that there was no general causative relationship between eye problems and reading and writing difficulties, although he did advocate "optimal treatment" of any eye abnormalities.

Drasdo (1988b) briefly reported the case of a 13 year old male who, following head trauma, suffered from a left hemianopia (with macula sparing) and reading difficulty; his reading speed one tenth of the normal. After an optometric and neuro-physiological examination the main problem was found to be an almost total absence of accommodation. Bifocals enabled the patient to read N5 fluently, although he never fully regained his former reading skill. Adler and Grant (1988), in a study that was described in Section 2.3.3, did not find any correlation between reading ability and the following variables: convergence insufficiency, fusional reserves, convergence excess, vertical imbalances, or strabismus.

Garzia et al. (1989) investigated the effect of nearpoint visual stress on pseudo-reading performance in normal subjects. They explained the "cloze" procedure for assessing psycholinguistic processing in reading; this is an active process of searching for meaning, and depends upon language processing skills. Their subjects were 19 "normal" optometry students, aged 22-33 years, who were unaware of the purpose of the experiment. They read cloze passages first with normal reading correction, and then with additional -2.00 DS lenses in front of each eye; a blind protocol was used. The subjects took significantly longer when using the lenses ($p < 0.03$), but their accuracy was not affected. The authors discussed possible sources of error (novelty, adaptation, or fatigue), and proposed a mechanism that explained their results in terms of attention; they also made the valid point that the results of studies with adults cannot necessarily be applied to children. The results showed a large inter-subject variation, possibly due to differing degrees of adaptation to the intervention; this could explain some of the conflicting literature on the association between visual disorders and reading ability.

Hung (1989) objectively measured vergence response velocities to computer generated convergent and divergent ramp disparity stimuli. He found slower and abnormal vergence responses in 2 dyslexic subjects; the small number of subjects and lack of matched controls and psychometric data precluded any statistical analysis or firm conclusions. The author suggested that this vergence deficit may be a feature of poor sequential processing (Pavlidis, 1981a), may have a neuro-anatomical origin, but may not be a causative factor in dyslexia.

Barnard (1990) suggested that convergence insufficiency or excess could contribute to learning difficulties in children who did not compensate by constant unilateral suppression; he thought this may be related to eye dominance. An unpublished multi-disciplinary study was briefly described that found significant evidence of a "visuomotor organisational anomaly" in RD; this anomaly was described as alternating fixation when convergence broke down. Three case studies were discussed that demonstrated oculomotor and refractive involvement in learning disabilities.

Wilkins and Neary (1991), in a study that is described in Section 4.2.2, found that 8 out of 20 individuals, most of whom had been diagnosed as dyslexic, had reduced amplitudes of accommodation. This measurement, however, was not related to their age and it appears that 5 of these had normal accommodation but gave a low reading because a refractive error had not been corrected. A surprising number of the subjects had a history of binocular vision problems (squint surgery in 1 case and orthoptic therapy in 4 cases). Several binocular vision tests were also carried out, but the results of these were difficult to evaluate in the absence of a control group.

Hall and Wick (1991) selected 111 students from a normal school who had IQs of over 70 (no test details or data were given) and were aged approximately 6 to 11 years. Subjects with strabismus or "clinically significant refractive errors" were excluded, although precise details were not given. The subjects' performance was assessed at the reading component of the Stanford Achievement Test and at the following optometric tests: V/A; a number reading task; accommodative amplitude, lag, and facility; heterophoria; fixation disparity; near point of convergence; and Titmus and Randot stereopsis. The ocular variables were correlated with the reading performance, both individually and in a multivariate analysis. None of these correlations reached significance, neither for the group as a whole nor for school year subgroups. The authors concluded that subtle defects in ocular functioning within a group of students with "normal vision" did not have an appreciable influence on their acquisition of reading skills. This paper did not include any data and very few details of the optometric tests were given. With this type of study design, very large numbers of subjects may be needed to reach significance; most estimates of the incidence of dyslexia would suggest that only about 11 of the children in this study would have been diagnosed as dyslexic.

2.4.1 Conclusions

Clearly, an unequivocal conclusion is inappropriate. The most frequent binocular vision anomaly in dyslexia appears to be poor convergence, and exophoria at near is another possible correlate; although some workers have found an increased incidence of esophoria. Fusional reserves (prism vergences) appear to be another correlate of dyslexia, and the uncertainty over whether positive, negative, or both types of reserves are affected may reflect the paradoxical findings concerning heterophoria. An increased incidence of accommodative dysfunction in dyslexia has also been found by several researchers. It should be stressed that other work relating binocular function to ocular dominance in dyslexia is discussed in Section 3.3; it will be seen that this work provides more evidence of vergence dysfunction in dyslexia.

The four most frequently occurring correlates in the studies cited so far have been poor convergence, exophoria at near, poor accommodation, and hypermetropia. An assessment of stereopsis is a test that should be impaired by, and hence might logically be expected to screen for, these 4 conditions (Reading, 1983, pp. 173-191; Pickwell, 1991). Yet the literature on stereopsis and dyslexia is far from conclusive (Robinson and Huelsman, 1953; Watts, 1970; Dunlop, 1976; Spooner, 1978; Bedwell et al., 1980; and Riddell et al., 1988b). This may be because some tests lack the necessary sensitivity (Reading, 1983, pp. 173-191; *see* Section 9.3), or owing to an inability to detect dynamic visual problems (Bedwell et al., 1980; Holland, 1987). An alternative approach is to use a test of visual information processing, such as a simulated-reading visual search task (Fendrick, 1935; Moseley and Lane, 1986); this is discussed in Section 2.8.

2.5 Eye Movements

This section is divided into 3 parts. First, selected research on the general nature of reading eye movements is presented. The evidence for, and analysis of, abnormalities of reading eye movements in dyslexia will then be presented. It will become clear that it is logical to evaluate whether such abnormalities also occur during visual tasks other than reading; this question will be addressed in the final part. Studies that have used eye movements to assess the efficacy of visual training are described in Section 2.6.2.

2.5.1 Introduction

2.5.1.1 Basic Types of Eye Movements and Their Measurement

Methods of recording eye movements have been reviewed by many authors (Tinker, 1946; Young and Sheena, 1975; Haines, 1980; Robinson, 1981). An early review by Tinker (1936) gave a list of the requirements that must be fulfilled by such methods; this list is still relevant today. The main types of eye movements and their characteristics have also been thoroughly described by many authors (e.g., Pavlidis, 1981a; Young and Sheena, 1975; Solomons, 1978; Robinson, 1981); the following brief description is taken from these texts.

When the eyes are steadily directed towards an object they are said to be under the control of the fixation reflex. The eyes are not completely steady, but make "slow drift" movements; each of these lasts about 0.2 s and extends over about 5' of arc. Superimposed on these are "high frequency ocular tremors", which extend through about 15" of arc and have a frequency of about 50 cps or more. The slow drifts tend to carry fixation away from the object of regard and this is corrected by a "micro-saccade"; these range from 1 to 20' of arc and are completed within about 0.025 s. The eye movements discussed so far have been described as physiological nystagmus.

Saccadic eye movements are probably the fastest movement in the body (Solomons, 1978, p. 140) and are also made when the eyes move from one fixation point to another; this action is described as the re-fixation reflex. "Pursuit" eye movements, which are similar to ocular drifts, occur when attempting to follow a slow-moving object; these start after a latent period of 150-250 ms and they then follow the target up to a speed of about 30° per second: saccadic movements can have a speed of up to 800° per second. Corrective saccades may compensate for inadequacies of pursuit movements. During the eye movements that have been described above, the angle between each eyes' fixation axes remains approximately fixed; when this changes, the eyes are said to have made a "vergence movement".

Collewijn et al. (1988) measured the binocular co-ordination of human horizontal saccadic eye movements in 3 "normal" subjects using a scleral sensor coil technique. Binocular saccades were not well yoked dynamically and showed an abduction-adduction asymmetry with a transient divergence of as much as 3° during horizontal saccades. Post-saccadic drift consisted of a vergence and version component and resulted in the fovea of each eye being guided towards the target. There was little intra- and inter-subject variability within their adult sample and the degree of yoking was decreased when the targets were viewed monocularly.

2.5.1.2 Reading Eye Movements

Eye movements during reading have also been described by many authors (e.g., Tinker, 1936; Solomons, 1978, pp. 152-153; Pavlidis, 1981a) and are illustrated in Figure 2.1. The eyes proceed along a line in a series of step-like saccades, which are separated by "fixation pauses". During the fixation pauses, information is acquired from the relevant section of text; the width of this section, normally measured in the number of letters, is termed the "perceptual span". At the end of a line the eyes make a large saccade, or "return sweep". Most saccades are in a left-to-right direction, but occasionally one is made in the opposite direction to return to previously read text, normally for cognitive reasons; these are called "regressions". Reading of more complicated, less comprehensible, text is usually associated with an increase in the number of regressions and fixations and a decrease in the perceptual span (this is inversely related to the number of fixations) and speed of reading.

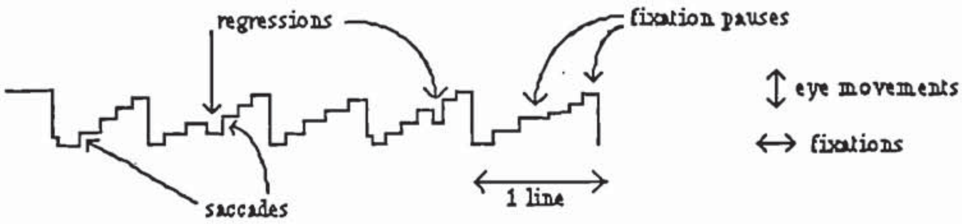

Figure 2.1 Schematic illustration of eye movements during reading. Further details are given in the text.

Tinker (1936) reviewed early research on eye movements in reading. He considered individual differences in eye movements, noting that: the pause duration was least variable measure; oral reading was less efficient than silent reading; eye movement habits in silent reading have become fairly stable by the age of 9 years; and, if intelligence was controlled for, good readers made fewer fixations and regressive movements per line and demonstrated a greater accuracy of the return sweep to the beginning of the succeeding line than poor readers. Stutterers were said to demonstrate irregular reading eye movements, and he felt that eye movement performance could not be improved by training.

Tinker (1936) next reviewed research on eye movements as a measure of legibility: the effect of reading text comprising narrow lines that eliminated horizontal saccades was to increase the number of words per fixation; and black print on white background was read faster than white on black. To obtain satisfactory reliability when recording eye movements whilst reading, he said that passages should exceed 20 lines in length.

Concerning the validity of this technique, Tinker (1936) noted a poor correlation with the results of reading tests and stressed that studies that made this comparison should use the same passages for both measures. He stated that the reading speed: was directly related to the fixation frequency; was fairly closely related to the regression frequency; but was not related to the pause duration. He finally reviewed the use of reading eye movement recordings in certain special reading situations: music, numerals, formulae, proof reading, spelling, examination questions, and foreign languages.

Tinker (1946) updated his 1936 review and included sections on: the effect of emotion, visual fatigue, illumination, and readability (this included the effect of various typefaces); and twin studies. He felt that the recording of eye movements in the reading clinic was unnecessary, and criticised the training of eye movements as only helping the child as much as reading the same passages in any other context. He argued that eye movements during reading merely reflected central processes, and advocated replacing terminology such as "eye movement patterns" with "perceptual sequences".

Underwood et al. (1988) monitored fixations during a sentence comprehension task to discover how subsequent text can be used to guide the eyes to future fixations. The patterns of eye fixations upon words with uneven distributions of information were observed, and it was found that more and longer fixations occurred when subjects looked at the informative parts, particularly at the informative endings, of words. The results supported the notion that eye movements are under the moment-to-moment control of cognitive mechanisms.

2.5.2 Reading Eye Movements and Dyslexia

Clark (1935) analysed vergence eye movements whilst reading in subjects with high exophoria; this study was discussed in Section 2.4. Taylor's (1937) study, which was also described in Section 2.4, found that underachievers at school made significantly more fixations and regressions whilst reading text for comprehension than "normal" children; however, it seems that the text was not matched to the children's abilities.

Knehr (1941) investigated whether reading efficiency was increased by monocular occlusion, and whether it was related to fixation frequency. His subjects were 16 visually normal postgraduates, who were assumed to have normal reading performance. Eye movements were recorded whilst the subjects read 4 paragraphs under the following conditions: binocularly, right eye only, left eye only, and bar reading. The conditions and order were rotated to minimise the practice effect and differences in the difficulty of the passages, which were not matched. The perceptual span was measured with a tachistoscope as the total distance along a line of print within which all the words, letters, and punctuation marks were reported correctly following a brief exposure. A tachistoscope was also used to measure the paracentral V/A.

The speed of reading, number of fixations and regressions, pause duration, and comprehension for the different conditions were not significantly different. The perceptual span was significantly reduced in the monocular condition, but this did not correlate with the fixation frequency; Knehr (1941) concluded that the perceptual span did not limit reading performance. Paracentral V/A was also reduced in the monocular condition, and this showed a slight correlation with the perceptual span. It was inferred from this that perceptual span was related to paracentral V/A and hence eye movement recording was not a useful accessory to teaching; however, the angular subtense of the perceptual span was not calculated. The eye movement recordings, for the monocular and binocular conditions, showed increased convergence at the beginning of each line and this was attributed to accommodative changes; an alternative explanation is that these were artifacts. These vergence movements were much greater than Panum's fusional areas and were therefore thought to be suppressed during normal reading. It was also concluded that it was pointless to train perceptual span and that the visual apparatus can feed information to the brain faster than the brain can use it.

Mosse and Daniels (1959) described "Linear Dyslexia" as when abnormal eye movements result in a person being able to read words but not lines of words. They stated that reading became a form of Pavlovian conditioned reflex that, if incorrectly learnt, was virtually impossible to correct. Linear dyslexia was said to be caused by reading comics and worsened by some teaching techniques; they further considered the effect of violence or sexually stimulating pictures in comics. This paper lacked results or quantitative data, except for one anecdotal case report, and an eye examination was only advised when there was a suspicion of defects (no criteria were given). The eye movements they described during comic reading seem to be equivalent to those that are used to analyse any visual scene (Yarbus, 1967) and would therefore phylogenetically and developmentally precede reading (Carpenter, 1988). In any case, most children who read comics are not dyslexic, although it seems quite likely that dyslexic children read more comics than usual simply because the pictures would help a RD child to follow the story.

Gruber (1962) described the Ophthalmograph, a non-linear photographic device for recording eye movements. He described one study that had found that better students made *more* regressions, presumably so that they can read more carefully. Gruber (1962) assessed the number of fixations and regressions, reading rate, span of recognition, and duration of fixation of 50 patients, whose age and reading performance were not given.

These variables only showed a low correlation with the ocular muscle balance (no details were given of the method of assessment). Inter-ocular eye movement differences were not analysed and the subjects' symptoms were not described. The author concluded that the Ophthalmograph was unreliable for assessing binocular co-ordination, but was useful as an objective measure of reading ability. He seems to have been the first researcher to note that static and dynamic binocular vision problems can occur independently.

Prechtl and Stemmer (1962) described a syndrome in children who demonstrated behavioural problems, poor school performance, and restlessness in which extra-pyramidal performance was disturbed, resulting in "choreiform movements". These consisted of slight, jerky, and irregular movements that occurred quite arrhythmically and irregularly in different muscles and were of sudden onset and short duration. A group of 50 children, aged 9-12 years, who suffered from this syndrome were subjected to a thorough neurological assessment, including electrophysiological and serological tests. The choreiform activity was clearly revealed by electromyographic analysis; occurred most clearly in stress situations; differed from myoclonic contractions; and always involved the muscles of the tongue, face, neck and trunk. The eye muscles were affected in 92% of the children, and this was said to result in disturbances of conjugate movement and difficulty in fixation and reading; details of the eye movement abnormalities and reading problems were not given. Parental reports suggested behavioural problems from an early age although functional development and intelligence were good (no details were given). Seven of the children showed epileptiform discharges on EEG examination and all showed short muscle artifacts, which were rare in a group of age-matched controls. There was a high incidence of pre-, para-, and post-natal complications, which included frequent epileptic attacks in 12% of cases. The authors felt that foetal distress or postpartum asphyxia were the most important aetiological factors and concluded that this syndrome was a form of minimal brain damage.

Prechtl (1962) briefly reviewed the evidence for minor neurological abnormalities in dyslexia, possibly resulting from "minimal brain damage". In addition to the points made by Prechtl and Stemmer (1962), it was reported that, in some cases of choreiform syndrome, errors in word recognition could be correlated with the occurrence of involuntary eye movements, as recorded by electro-oculography (EOG). The author implied, therefore, that choreiform eye movements may be a cause of RD.

Goldberg and Arnott (1970) used an Electronystagmograph, which from their brief description appears to be an EOG device. They examined the eye movements of 25 dyslexic children and an unspecified number of normal controls; no other details of these subjects or diagnostic criteria are given. Recordings were taken whilst reading easy text and complex text with and without an adult's help, and then easy and complex text again, but after the children had been taught the difficult words in the passage. The dyslexic group demonstrated irregular eye movements (no analysis of the type of irregularity was given) whilst reading the complex text; the degree of irregularity varied with the verbal difficulties in the reading material. The eye movements were said to improve towards the "normal range" when the children were helped or the difficult words were taught in advance; the interpretation of the eye movement traces seems to have been qualitative. The authors concluded that eye movements in reading were secondary to comprehension, not vice versa.

Zangwill and Blakemore (1972) studied one patient who was intelligent, ambidextrous, and a congenital dyslexic. Assessment of his eye movements during reading showed a reversed staircase pattern, with the patient attempting to read from right to left; when he did manage to read from left to right the trace was unstable and irregular. Griffin, et al. (1974) assessed the saccades during reading and non-reading tasks of 13 learning disabled and 13 control subjects; this study is described in Section 2.5.3.

Adler-Grinberg and Stark (1978) stated that eye movements can be used as an indicator of higher-level brain processing, but only once the basic normality of eye movements has been established. They used a limbal tracking device to give a sequential display of the eye position superimposed on the stimulus image; qualitative and quantitative analysis of the results were carried out by direct measurement. The subjects were 25 dyslexic children, whose reading age was a mean of 1.5 years behind their chronological age, and 15 controls, whose reading age was on average 1 year advanced. The groups were said to have average IQ, were matched for age and IQ, and the children read material commensurate with their reading level. The authors found that the dyslexic group had a 20% increase in their fixation duration, a 25% decrease in their fixation span (perceptual span), a similar frequency of regressions, and a 36% slower reading rate compared to the control group.

Pavlidis (1981a) reviewed research on erratic reading eye movements, which were said to be associated with: reading difficulties; poor comprehension; difficulties in maintaining fixation; difficulties in sequentially fixating words or lines of text; fatigue; and headaches. He described his study of 9 dyslexic and 9 matched control children, which had found highly significant differences between the groups in some eye movement characteristics, particularly the number, size, and position of regressions. The author discussed whether the erratic eye movements were the primary cause of the reading disability, were secondary to a central comprehension problem, or were the symptoms of a central deficit;

he favoured the latter explanation and described the deficit as "sequential order disability". Pavlidis (1981a) next described his experiment to investigate the following hypothesis:

> "if the dyslexics' erratic eye movements are the manifestation of the difficulty they have with the text, then when they read material too easy for them their eye movements should become 'regular'. Backward readers of the same chronological and reading ages should have similar eye movements to dyslexics. However, the other readers' eye movements must be expected to become 'irregular' when they read a text too difficult for them."

This hypothesis is weakened by the possibility that a dyslexic person may have developed abnormal eye movement characteristics whilst reading as a method of compensating for his reading disability; hence, his habitual reading eye movements may be quite different to those of an experienced good reader. Pavlidis (1981a) investigated his hypothesis in a study of 14 dyslexic children, 17 backward readers, 16 normal readers, and 12 advanced readers; the groups were shown to have significantly different eye movement parameters during reading. The author went on to investigate eye movements during non-reading tasks (*see* Section 2.5.3).

Poynter et al. (1982) related the reading ability of 74 children, aged 9 to 11.5 years, to the following oculomotor functions: forward-fixation frequency; regressive-fixation frequency; and average duration of fixation. The subjects performed 2 reading tasks, one easy and one difficult, and a digit reading task (isolated, well-spaced, digits). Eye movements were monitored by an infra-red device and were analysed manually. Forward and regressive fixation frequency were both inversely related to reading ability for prose-reading, but not for digit-reading. This finding reached significance, with or without controls for verbal intelligence; each of these variables accounted for 8% of the variation in reading ability when the effect of verbal intelligence was removed. The results suggested that eye movement abnormalities were related to language skills rather than fixation skills.

Pirozzolo and Hansch (1982) briefly reviewed the role of eye movements in the neurophysiology of RD and noted that some dyslexic children had difficulty with return sweeps. They concluded that dyslexia was sometimes associated with a deficit in basic spatial-oculomotor function, but that this was an effect of the underlying "pathophysiology that causes dyslexia" rather than the cause of the RD.

Eskenazi and Diamond (1983) used an infra-red system to assess the eye movements of 15 dyslexic children, whose reading age was at least 2.4 years behind their mental age, and 15 age- and IQ-matched controls. The dyslexic group made significantly more fixations and regressions, paused for significantly longer at the beginning of a line, and had a 50% smaller perceptual span. There was no difference in the number of corrective movements at the beginning of a line, or in the number of times they regressed back to a former line.

Wilkins et al. (1984) showed that when some individuals viewed certain striped patterns they may experience eyestrain and headaches. Wilkins and Nimmo-Smith (1984) hypothesised that since successive lines of printed text comprise a pattern of stripes, these stripes may provoke some of the eye-strain and headaches that are attributed to reading. Wilkins and Nimmo-Smith (1987) measured the spatial properties of printed text and showed that these did resemble a grating that might elicit pattern glare. Wilkins and Nimmo-Smith (1984) devised some aids, similar to a typoscope in construction, to limit the number of lines viewed to about 5 lines. One third of their volunteers (who were predisposed to asthenopia from reading) derived substantial benefit from the aid. They referred to a paper in preparation, which showed that:

> "patterns of stripes surrounding a fixation target can increase the SD of the position of the eye. The SD varies considerably from one person to another, and people with unstable fixation tend to see more illusions. Perhaps in attenuating the pattern of stripes the reading aid enables people with relatively poor oculomotor control to find words more readily."

It is possible that this fixation instability could result in abnormal eye movements in RD. This may relate to the use of tinted lenses (*see* Section 4.4.2)

Ciuffreda et al. (1985) studied the eye movements of 3 patients with varying types of ocular pathology (*see* Section 1.8) and one patient with congenital dyslexia. The latter patient was a 32 year old female, whose reading eye movements were recorded whilst 'reading' a dot pattern and print of differing degrees of difficulty. The eye movement data are difficult to interpret owing to the lack of normalised data for the reading passages. The patients with acquired and congenital dyslexia had normal fixation durations, but made an excessive number of fixations. Ciuffreda et al. (1985) interpreted this as implying that the primary sensory aspects of fixation were normal and the abnormality occurred in higher level processing of the textual information.

Holland (1987) believed a major problem in dyslexia was divergent drifts or overconvergent spasms, sometimes occurring within Panum's fusional area, and causing confusion or suppression. An unstable reference eye was thought to worsen these problems; although these theories seem plausible, little evidence was given to support them.

Voke (1987) reported the contribution to the 1987 Child Vision Research Conference by Dr. Hagemans. He used an infra-red device to record monocular *and binocular* eye movements during reading and found that some cases of dyslexia had poor binocular co-ordination; they made abnormally small reading movements with one eye, with the other becoming completely redundant in the reading task. Intensive binocular training over 3 months improved the reading ability and resulted in better conjugated eye movements. No data for this study were reported; it is possible that the eye movement results were artifacts.

Singleton (1988) reviewed the early diagnosis of developmental dyslexia, including research on eye movements. He concluded that abnormal eye movements in reading were the result of abnormal reading development and/or a lack of disciplined reading experience and that the predictive and discriminatory power of eye movement analysis for dyslexia had not yet been unequivocally demonstrated.

Hardman et al. (1989) investigated the effect of diet on the reading eye movements of 13 dyslexic people, aged 7-28 years. The eye movements were analysed after the subjects had been on a high sugar "junk food" diet for 4 days and they were then placed on a no-sugar diet for 5 days. The eye movements were re-tested, after which the subjects were given a provocative sub-lingual challenge of either sugar, corn, ethanol, or saline, followed by a re-analysis of the eye movements. The number of fixations and regressions increased both on the 4 day sugar diet and on provocative sugar testing ($p < 0.05$) and the authors concluded that sugar influences the neurological system, hence altering either cognitive functions, motor control, or attention.

This study, unfortunately, suffers from several methodological weaknesses that will now be described. The subject selection criteria were vague and non-specific and the question of hyperactivity in the group was not addressed. Eleven of the subjects were hypersensitive (the relevant allergens were not stated); this highlights the need for controls, preferably with a similar ratio of atopic individuals. The authors stated that the study was double blind, but it seems likely that the children could taste which of the sub-lingual stimuli they were given. Similarly, when American children are placed on a "junk food" free diet for 4 days, it seems highly improbable that they would remain unaware of this. The reading material for the eye movement testing was not described and the analysis of the fixations and regressions does not appear to have been carried out according to a blind protocol. Further research is warranted in case this theory explains some of the inconsistencies in the results of other studies of eye movements in dyslexia.

2.5.2.1 Conclusions

The general consensus appears to be that dyslexic children make an increased number of fixations, particularly regressions, when reading. Other aspects of reading eye movements may also be abnormal. There are 3 potential explanations for these findings: they are the cause of the RD; they are the caused by the reading difficulties; or they are an effect of a higher level problem that also, through another mechanism, causes the RD (e.g., a sequencing problem). These questions can, to some extent, be investigated by studying the eye movements during simple, non-verbal tasks; studies that have used this paradigm will now be described.

2.5.3 Eye Movements in Non-Reading Tasks and Dyslexia

Gilbert (1953) questioned whether the oculomotor efficiency that was necessary for reading eye movements improved with age. He elicited this type oculomotor behaviour without involving comprehension by asking subjects to "read" 3 cards of randomly spaced single digit numbers. They also read 2 cards of prose and their eye movements were photographically recorded during these tasks. The recordings were analysed principally for the fixation duration, and regression and fixation frequencies. He examined 473 children who were randomly selected from a normal population between the ages of 6 and 14 years. He first compared the eye movement characteristics of yearly age groups; the results were difficult to interpret because the same tasks were used for all ages. The development of eye movement skills for prose and digit reading were similar but there were large individual variations. The frequency of fixations and regressions for digit and prose reading at each age level were closely related but were not predictive of one another. Intelligence was strongly correlated with, but not predictive of, oculomotor skill whilst reading prose and was slightly correlated with that during digit reading. The analogous correlations with reading test results were similar but less significant. The eye movement characteristics during digit reading of 6 year old pre-readers were similar to those of older children, but showed a much larger inter-subject variation. The eye movement characteristics of college students were found to be similar, but slightly better, than those of children.

This study suffered from a few methodological weaknesses: different intelligence tests were used for different children; it was not clear whether the eye movement recordings were monocular or binocular, or how they were calibrated; the younger children found the prose passages very difficult so that many records had to be discarded because of poor comprehension; and the effect of intelligence was not controlled for. In many respects, however, this study was far ahead of its time and some results were particularly interesting. When the subjects were grouped according to their eye movement performance the lowest quartile were *much* worse than the others. This may suggest that there was a sub-group with either: eye movement defects; low intelligence preventing them from understanding the task; or who were inattentive or unco-operative. It is surprising that the basic eye movement skill of digit reading was still improving up to the age of 14 years.

Griffin et al. (1974) examined the saccadic eye movements of 13 learning disabled subjects, whose reading was 1-5 years below grade, and 13 controls, whose reading was "above average"; the mean age of both groups was 10.5 years. The eye movements were assessed whilst the subjects "read" targets that comprised: 25 pictures; 25 dots; 2 widely spaced words; 5 words; and reading material, with comprehension questions, that was set at the child's level. The dyslexic group made significantly more fixations with the dot card and significantly more regressions with the dot, 5 word, and reading card. This study suffered from the following weaknesses: poor subject selection criteria; a blind protocol did not seem to have been used to analyse the eye movement traces; and some of the significance levels from which conclusions were drawn were unusually high. The authors thought that if a subject made increased regressions with material set *at their reading level* this demonstrated saccadic abnormality; an alternative explanation is that excessive regressions could become an habitual feature of reading eye movements to compensate for a central language dysfunction. The authors also concluded that the poor readers fell into 2 groups, those who sequenced saccades too rapidly, and those who sequenced them too slowly. From this they reached, without justification, the somewhat confusing conclusion that "a disorder of saccadic eye movements is a problem of microsequencing". They further stated, without giving any evidence, that remediation by visual training helped their subjects.

Lefton et al. (1978) examined 24 subjects from each of the following groups: RD adults; RD children, aged 7-9 years; normal readers, aged 7-9 years; and normal readers, aged 10-11.5 years; the RD subjects were diagnosed by a school psychologist. The authors measured the frequency of fixation, duration of fixation, number of errors, and fixation position with an infra-red device whilst the subjects searched for a certain sequence of letters in a block of random letters. Lefton et al. (1978) argued, controversially, that children's normal reading is untimed, and they therefore did not use a time limit. They found that when attention had to be sustained for more than 5 s the RD subjects' search pattern became erratic. They concluded that these subjects can discriminate letters but have a deficit in cognitive operations during sustained attention; an alternative explanation for the results might be poor short-term memory in the RD group. The researchers did not state whether the number of errors made by the RD group was significant enough to be diagnostic.

Adler-Grinberg and Stark (1978), in a study that was described in Section 2.5.2, studied eye movements during: a simple visual search task; viewing pictures; and following a target that stimulated saccades and smooth pursuit movements. The ocular behaviour in response to pictorial visual tasks was analysed in terms of fixation location, fixation duration, and appropriateness of areas fixated; no significant differences were found between the 2 groups of 25 poor and 15 good readers. The search task of identifying a geometric shape was also performed similarly by both groups. The authors found the dyslexic group's saccades were normal, but that their smooth pursuit movements were significantly more likely to demonstrate saccadic pursuit or cog-wheeling than those of the controls. The finding of normal saccades contradicted previous research; this was explained by differences in methodology and/or subject selection. Pursuit eye movements are not normally used during reading (Hartje, 1972) and the authors noted that this saccadation was also found in people who were inattentive, fatigued, or under the influence of certain drugs. Adler-Grinberg and Stark (1978) concluded that:

> "the information-processing obstacle appears to lie beyond visual perception, perhaps in the language area itself, and the dyslexic's characteristic deficit must, therefore, involve the integration of the visual input into the language-acquisition function."

Elterman et al. (1980) criticised previous research on eye movements in dyslexia for not including "symbol reading" and not assessing vertical eye movements. Their subjects were 1 "normal" adult, 1 "normal" child, and 5 dyslexic children. They recorded the horizontal eye movements of the right eye, and the vertical eye movements of the left eye during the following tasks: reading material one year below, one year above, and at the level of their reading ability; and reading X's. Two of the dyslexic subjects had difficulty with sequential eye movements for both the symbols and the reading passages. This study suffered from the following methodological weaknesses: inadequate selection criteria were applied; 2 of the dyslexic subjects had epilepsy; measuring the vertical eye movements from one eye and the horizontal from the other would invalidate the results if the eyes became dissociated; the lower eyelid was held down with tape; there was no quantitative analysis of the eye movements and only certain parameters were analysed qualitatively; the one normal reader was in fact hyperactive; and few details were given of the eye movement apparatus.

Pavlidis (1981a) reviewed his studies on dyslexic children's erratic eye movements in non-reading sequential tasks. He stated that the most vital process in reading was sequential ordering and listed a number of clinicians who had found this to be a fundamental deficiency in dyslexia. His first sequencing experiment involved 12 dyslexic children, aged 12-16 years, and 12 controls of similar age; presumably the groups were otherwise unmatched. The children's eye movements were assessed using a photoelectric device whilst fixating the illuminated one of 5 lights that came on in sequence. This pilot study, which was described in more detail by Pavlidis (1981b), showed that the dyslexic group made significantly more regressive movements.

Pavlidis (1981a) then reviewed his studies that had compared dyslexic children with backward readers; this paradigm was criticised in Section 2.5.2. The subjects were the same as in his second reading experiment (*see* Section 2.5.2) and the results were analysed using a "blind" procedure. The dyslexic subjects were again unable to accurately follow the sequentially illuminated lights: all other subjects, including the backward readers, were able to perform this simple task very accurately. The most revealing parameter was the percentage of forward and regressive fixations and the dyslexic subjects made a similar percentage of regressions when following the lights as in reading; all the other groups made far fewer regressions during the former task. These results were highly significant; this study was reported in more detail by Pavlidis (1985).

Pavlidis (1981a) concluded that dyslexic children have sequential eye movement control difficulties that were independent of memory, although they may also have a memory problem. He felt the most likely cause of dyslexia was a "miswiring" in the brain resulting in a disruption of sequential order and he proposed that his sequential light test be used as a diagnostic test for dyslexia. In all of his studies Pavlidis (1981a) seemed to assume that dyslexia was homogeneous in aetiology; it could be that he was merely looking at one sub-type of dyslexia. His subjects were obtained from many sources and it is possible that a referral bias occurred. All of his eye recordings appear to have been monocular, no eye examination results were quoted, and no vertical eye movement results were given, although it was stated that these were obtained (Pavlidis, 1981b).

Kowler and Martins (1982) compared the basic eye movements of 2 preschool children, aged 4.5 and 5 years, with those of an adult; no subject details other than age were given. They found that the children exhibited more fixation instability, an increased velocity distribution of smooth pursuit movements, and worse control of saccadic timing for rapidly changing step targets. They concluded that the children had incomplete oculomotor development and suggested that the eye movement characteristics of adults may imply overlearned motor habits. This paper did not include any statistical analysis and there was little quantitative analysis of the data. Kowler and Martins (1982) did not consider that attentional factors may have confounded their results, although in any case, one might expect to find decreased motor control in preschool children. It is also puzzling that these authors expressed the noise level of their dual Purkinje-image apparatus in terms of one standard deviation obtained from an artificial eye; it might have been more appropriate to adopt 2 standard deviations from a human eye and it seems unlikely that a second Purkinje image could have been obtained on a model eye.

Poynter et al. (1982) found that forward and regressive fixation frequency were both inversely related to reading ability for prose-reading, but not for digit-reading. This suggests that fixation frequency is related to language skills rather than oculomotor or sequential ordering skills. This study, which disagrees with Pavlidis (1981a, b and 1985), was described in Section 2.5.2.

Pirozollo and Hansch (1982) reviewed the literature on eye movements and dyslexia and concluded that: "some dyslexics do have deficits in basic spatial-oculomotor function." They felt that this was owing to the underlying pathophysiology that causes dyslexia. Since human beings effectively function in 2 planes, space and time, a spatial disability combined with the temporal disability described by Pavlidis (1981a) might be expected to produce a rather less specific disability than dyslexia.

Stanley et al. (1983a) repeated Pavlidis' (1981b) study. They used 15 dyslexic children and 15 controls, all from the same independent school, who were matched for age (mean 12.5 years) and non-verbal intelligence. They found that, with the possible exception of 1 subject, the eye movements of both groups in a simple tracking task were similar. They concluded that dyslexic children differ from controls in their processing of linguistic text and not in general perceptual processing and that Pavlidis' (1981a) test may be appropriate for identifying those dyslexic people with a dyseidectic (visual) syndrome, but not for other types of dyslexia.

Pavlidis (1983) highlighted several methodological differences between Stanley et al.'s (1983a) replication and his original study (Pavlidis, 1981b). Stanley et al. (1983b) commented on these, noting that their results agreed with those of Adler-Grinberg and Stark (1978).

Brown et al. (1983a) investigated the sequential tracking of 34 dyslexic and 33 control boys, aged 10-12 years. The groups were defined using a modification of the Myklebust formula ([2 x reading age] / [chronological age + mental age]). The number of predictive eye movements (anticipating an imminent movement of the target) was calculated. The total number of saccades was counted and the eye movement traces were additionally analysed by a "blind" experimenter for the quality of eye tracking. Brown et al. (1983a) found that the predictive eye movements were similar in the groups, although there was a large variation within each group. The quality of tracking in the 2 groups did not differ significantly and the control group made significantly *more* saccades. Brown et al. (1983a) explained the difference between their and Pavlidis' (1981a) results:

> "Pavlidis' task required fixation on the target at each location for 1 s, except at the extreme left and right, when it was presented for 2 s. Many extra saccades appear to be made at these turn-around points, as if the subject were anticipating that the target should move. Our test paradigm, which was designed to examine this anticipatory or predictive eye movement behavior, presented target steps regularly every 800 ms and was not affected by variations in task pace which may have provoked extra saccades in Pavlidis' RD group. Why only his RD group made these extra saccades is unclear to us. One possible explanation is that this RD group had some attentional deficit which was provoked by his task and was not apparent in our carefully screened test populations."

Brown et al.'s (1983a) paper lacked some methodological details, they only recorded horizontal eye movements, and the left eye was occluded throughout the experiment; this might mask a binocular vision problem. It is unfortunate that these researchers did not analyse regressions separately; this was a failure to investigate Pavlidis' most significant finding, although it seems unlikely that this parameter would alter significantly without influencing the total number of saccades. This research, nevertheless, did seem to justify the authors' conclusion that "eye movements do not hold the key to dyslexia".

Eskenazi and Diamond (1983) assessed eye movements with an infra-red device whilst subjects performed a search task for pictures or Greek symbols. This study, of 15 dyslexic children and 15 matched controls, was described in Section 2.5.2. The dyslexic group performed significantly slower when the target was tilted ($p = 0.03$); this intervention improved the performance of the control group. The direction of eye movements did not differ in the 2 groups and this was said to imply that regressions during reading were due to comprehension problems; c.f., Pavlidis (1981a,b).

Fowler et al. (1985) briefly described their experiments measuring the eye movements, with a limbal tracking device, during the Dunlop Test; these were described more fully by Stein et al. (1988) and are discussed in Section 3.3. They found that some dyslexic children could not converge or diverge to follow small fusional stimuli, but instead made inappropriate conjugate pursuit movements so that one eye soon ceased to foveate and suppressed. This lack of control, after as little as 0.5°, resulted in diplopia when suppression was released.

Ciuffreda et al. (1985) studied 1 congenital and 3 acquired dyslexic people. The subjects with acquired dyslexia had fundamental eye movement abnormalities; these were described in Section 1.8. Eye movements were recorded whilst the subjects "read" a paragraph of dots (8 dots/line, 7 lines) and a moving spot of light was used to generate fixational, saccadic, and pursuit movements. The subject with congenital dyslexia showed normal eye movements when following the spot, but demonstrated an excessive number of regressions and an irregular eye movement pattern when reading the dots or text. The authors concluded that the fundamental problem in this case was poor sequential tracking.

Swanson (1987), in a review, supposed that eye movement abnormalities in people with a learning disability were indirect reflections of their information processing difficulties. Singleton (1988), in his review of the early diagnosis of developmental dyslexia, felt that Pavlidis' sequential tracking test could only have an application for the minority of dyslexic children with a clearly visuo-spatial problem. He also pointed out that younger children's performance at this test should be investigated before it could be used as a predictive test for any type of dyslexia. Singleton (1987) highlighted the work of Eskenazi and Diamond (1983), which he believed suggested that dyslexic subjects have difficulties in processing directionally confusing information and/or sequential memory.

Garzia et al. (1990) designed an inexpensive test to quantitatively evaluate saccadic eye movement skills in RD children: the Developmental Eye Movement test (DEM). This comprised 2 subtests, one with 2 vertical columns of numbers, and the other with numbers randomly arranged in a horizontal spatial array; the subjects were timed whilst they read out the numbers. The first test was a control condition to partition out the effect of visual-verbal automaticity, and the ratio of horizontal to vertical subtest performance was claimed to differentiate poor oculomotor function from a primary automaticity deficit. The test seemed to be based on the assumption that poor "oculomotor skills" will have a greater effect on randomly spaced horizontal saccades than on regularly-spaced vertical saccades. The author obtained normative data on 556 schoolchildren, who were aged between 6 and 13 years and were only selected as having "normal" nearpoint acuity. Four percent of the subjects were unable to carry out the test, and it is not clear what action the experimenters took when a subject lost his place. The intra-subject and inter-examiner reliability were found to be within normal statistical limits; although full data were not given.

A further study of 58 children found a significant correlation between all DEM subtests and the Wide Range Achievement Test; this would seem to indicate that the DEM test result was confounded by intelligence. The test was then applied to 60 learning disabled (LD) children, who were said to have normal IQs, and the results were compared with those of the normative study; the groups were not matched for intelligence. The subjects were divided into 6 age groups and the LD children performed significantly worse at all aspects of the test, including, for 3 of the age groups, the ratio of horizontal to vertical subtests. The authors' conclusion that the LD group "had an additional difficulty when eye movements were required" would seem invalid since eye movements were required in both subtests. An alternative hypothesis is that the LD children performed worse at all subtests owing to lower intelligence, but demonstrated relatively poorer performance at the horizontal subtest because it was a harder task. This hypothesis could also account for the authors' observation that the ratio scores declined steadily with increasing age. An interesting feature of the DEM test is that the randomly spaced subtest requires a greater degree of saccadic programming, which is thought to be mediated through the transient visual system (*see* Section 2.7.1). Before the DEM test is recommended for clinical use further research may be required, including studies to see if the test can detect subjects with pathological saccadic dysfunction (*see* Section 1.8) and studies to investigate the relationship between the test results and line and single word reading in a tachistoscope. Future research should match groups for intelligence, and could also record eye movements.

2.5.3.1 Conclusions

At the end of Section 2.5.2, 3 potential explanations for abnormal reading eye movements in dyslexia were proposed: they are the cause of the RD; they are the caused by the reading difficulties; or they are an effect of a higher level problem that also, through another mechanism, causes the RD (e.g., a sequencing problem). Although the studies in the present section are equivocal, most workers have not found abnormal non-reading eye movements in dyslexia. The evidence therefore supports the tentative conclusion that abnormal reading eye movements in dyslexia are the effect of cognitive difficulties with text.

2.5.4 Research on a Cerebellar-Vestibular (C-V) Deficit in Dyslexia

Frank and Levinson (1973) reported that of 115 consecutive dyslexic children who had been referred for psychiatric evaluation, 97% had evidence of C-V dysfunction. Neurological examinations on 17 randomly selected members of this group were said to reveal cerebellar deficits in every case; no details of the neurological tests or results were given. Thirty children from the original group were selected for ear, nose, throat, audiographic, and EOG examinations; it is not clear whether these were randomly selected. The EOG examinations were said to be abnormal in 26 of these who revealed spontaneous and positional nystagmus, dysmetric ocular pursuit, and asymmetric functioning of the vestibular apparatus in the presence of normal ear, nose, and throat, and audiographic findings. Most of Frank and Levinson's (1973) paper was devoted to the development of a theory based on the role of the C-V circuits in stable ocular fixation and sequential scanning of letters and words. They thought that C-V dysfunction and subclinical nystagmus resulted in "letter and word scrambling", which in turn caused the comprehension problems in dyslexia. The incidence of dyslexia from C-V dysfunction in one school year of Staten Island was 2%, and the medical treatment of this condition was advocated. Their research, which did not include a control group, was not described in detail.

Frank and Levinson (1975) described the patients who suffer from this C-V dysfunction as "dysmetric dyslexics and dyspractics". The diagnosis of this condition was based on neuro-psychiatric tests and the "blurring speed", which is the minimum speed of movement of a certain target in relation to a specified background in order for the target to become blurred. The authors said they had proved that dysmetric dyslexics have C-V dysfunction, sub-clinical nystagmus, poor ocular fixation, and poor sequential scanning, compared with normals. They believed that current views on the aetiology of dyslexia were erroneous and stressed that reading difficulty is a non-essential symptom of dyslexia. They criticised conventional thinking on the male/female ratio in dyslexia and used a theory of learning processes in the cerebellum to support their unorthodox contention that dyslexia is self-limiting and its incidence decreases with time. Incidence was stated as 1-2%, and they said the cause could be genetic, viral, toxic, allergic, or emotional. Treatment was oculomotor exercises, modifying reading technique, and sea-sickness medication. This paper was a brief synopsis of Frank and Levinson's ongoing research, without details or statistical evidence. The fulcrum of their theory seemed to be the blurring-speed test, and the assumption that this relates to C-V dysfunction and dyslexia.

Frank and Levinson (1976) described some of their research in more detail . They believed that C-V dysfunction can be compensated for, and the degree of compensation varies form person to person and increases with time. In acute and poorly compensated cases, clinical nystagmus led to "an oscillating and unstable optical fixation (i.e. 'blurred' vision, oscillopsia, etc.)." The authors inferred that sub-clinical nystagmus was suppressed during ocular fixation and was present when the eyes were closed; they referred, without details, to evidence of this from EOGs. It would be interesting to investigate reading speeds in cases of conjunctive nystagmus which, according to the author's theory, should be notably reduced (in contrast to normal clinical observations). Frank and Levinson (1976) found that 97% of 250 dyslexic individuals (no details or selection criteria were given) had C-V dysfunction (no diagnostic criteria were specified), but none had clinical nystagmus. They theorised that any significant reduction in the blurring speed was a direct function of the subclinical nystagmus and stated that: "the data statistically proves the existence of a subclinical nystagmus in dysmetric dyslexia and dyspraxia." It is not clear to which data they refer, and no statistical analysis appeared in the paper. They identified some "fallacious assumptions" in dyslexia research analysed the "scientific neurosis" that have prevented other researchers from arriving at their conclusions. Some case histories were appended.

Brown et al. (1983b) assessed vestibular function in 34 dyslexic and 33 control boys who were matched for age and performance IQ. The children were free from neurologic, visual (full details of the examination were not given), and hearing deficits. The subjects' eye movements were recorded whilst they were sinusoidally rotated at low frequencies in total darkness. There were no significant differences in the gain, phase, or asymmetry of the eye movements of the 2 groups. The authors concluded that there were no clinically measurable differences in this aspect of vestibular function between their carefully selected samples.

Raymond et al. (1988) studied 6 dyslexic children with neurological signs of cerebellar dysfunction and 6 age-matched controls; no diagnostic criteria for the dyslexia or psychometric data were given, and the controls were not matched for sex or intelligence. The subjects' eye movements were recorded whilst they viewed a 1.4° square target. This was presented on a computer screen against either a uniform background or a moving grating that was designed to maximally stimulate the optokinetic system. The target induced saccadic eye movements by sequentially alternating between 2 positions. The dyslexic group exhibited significantly more fixation instability when the target was stationary. The presence of the grating background produced a significant increase in fixational error for the dyslexic group relative to the control group. The saccadic accuracy and latency of both groups were similar, and the authors concluded that saccadic eye movements were normal in the dyslexic group. The fixation stability of the control group was within the 0.5° resolution that was claimed for the apparatus, but some controls were said to exhibit a fixation instability of up to ± 1°; it was suggested that this could impair visual processing during reading.

Raymond et al. (1988) noted that their target was too large so that the children had to be asked to fixate one side of the square. Their results could be attributed to attentional problems resulting in the dyslexic group changing their fixation from one side of the square to the other. The normal saccadic latency in the dyslexic group may mitigate against this argument. The fixation instability was characterised by square wave, flutter, and nystagmoid movements. Raymond et al. (1988) suggested that this, together with the decreased suppression of oculokinetic nystagmus, were further signs of cerebellar dysfunction in the dyslexic group. They concluded that the assessment of RD children should include the evaluation of cerebellar function. Horizontal eye movements were recorded from one eye and vertical from the other and the subjects were not given a full eye examination. The effect of binocular control on the results, therefore, is uncertain.

This study suffered from some further methodological weaknesses: the control subjects were not tested for neurological signs of cerebellar dysfunction; and the effect of attentional problems on the neurological tests was not considered.

The theories on C-V dysfunction are controversial, taking the supposed origin of RD out of the cerebrum and placing it in the cerebellum. The sole rigorous investigation in this section, by Brown et al. (1983b), did not support this hypothesis.

2.6 VISION TRAINING

Vision training for dyslexia is relatively uncommon in the UK. The basis of this treatment, therefore, will be briefly reviewed together with some studies that, although not specifically relating to RD, are particularly relevant. The research and reviews on vision training and dyslexia will then be covered.

2.6.1 Introduction

To understand some of the vision training techniques it is necessary to briefly describe the philosophy of behavioural optometry (Gilman, 1990). This discipline started with the work of Dr. A.M. Skeffington through the USA "Optometric Extension Program" in 1928. This philosophy uses the word "vision" to indicate the total concept of vision information processing in the context of its integration in all human processing (Gilman, 1990). Gilman (1990) described another basic concept of behavioural optometry: that vision is learned and therefore trainable. He described Skeffington's classification of vision into 4 processes: *identification* is the whole perceptual process of identifying something in the visual field; *centering* is the total ability, including vergence, of knowing where something is located in the visual field and then being able to attend to it; *posture-movement* reflects developed orienting and movement skills which affect form, depth, and spatial perception ability; and Skeffington later included speech-audition processes since he felt these were necessary for the full development of vision. The normal visual development of deaf and dumb children may bring the latter point into question. Gilman (1990) described the use of nearpoint prescriptions, vision therapy, and environmental modification to address the stress of nearpoint performance; it was emphasised that these would improve performance (e.g., reading), but not necessarily V/A. He suggested that untreated nearpoint stress may be the cause of "whole body stress" and many vision problems, including myopia. The philosophy of behavioural optometry was described as preventative. Behavioural optometry is used to promote visual information processing in individuals who do not appear to have a specific ocular or vision defect (Gilman, 1990; Hendrickson, 1990). Helveston (1987) pointed out that most of the research that is used to support these theories have not adhered to standard scientific methods of evaluation; the cynical could suggest that this philosophy not only facilitates the "legitimate" optometric treatment of patients with normal V/A, but also of people with no signs or symptoms of visual dysfunction.

Wittenberg et al. (1969) measured the stereopsis of 16 subjects and divided them into control and experimental groups. The latter underwent training in which they repeatedly adjusted one virtual object to lie in the same fronto-parallel plane as another virtual object. After training, the stereopsis of both groups had improved, but to a significantly greater degree in the experimental group. The authors concluded that stereopsis could be improved by training.

Liu et al. (1979) described case studies of 3 young adult females who had reported difficulty focussing at near. They were treated with conventional eye exercises to train the response to step and ramp changes in the accommodative stimulus. After treatment: symptoms were reduced; accommodative facility was improved; and the latency, velocity, and quality of accommodation, recorded by an objective optometer, had improved. The lack of a control group with a placebo treatment means that some of the results could be explained by practice effects.

Daum (1984) carried out a retrospective analysis of the records of 114 orthoptic patients with accommodative dysfunction to construct a model of the results of orthoptic treatment. He showed that a linearised discriminant function using the age and AC/A ratio of the patient was effective in postpredicting the success category of 60% of a calibration sample of 99 patients.

Grisham et al. (1991) described a small controlled study and 3 case studies that used an objective technique to assess the efficacy of training fusional vergence. Step vergence stimuli of decreasing duration were presented to subjects on a modified haploscope whilst vergence eye movements were recorded with a limbal tracking device. The subjects who were given vision training showed a marked improvement, both objectively and with subjective prism vergences, that was associated with a complete resolution of symptoms. Subjects with vergence dysfunction who did not receive treatment did not improve on either measure, although a visually normal subject showed a slight improvement in vergence function on treatment. The improvement was sustained for at least 6 months after the therapy stopped, except for 1 subject who ended his treatment prematurely. This study, despite using small subject numbers and failing to give selection criteria, does represent objective evidence for "vergence orthoptics".

2.6.2 Vision Training and Dyslexia

Keogh (1974) carried out an objective review of optometric vision training programs for learning disabled children. These programs varied; some only involved eye exercises, whilst others went much further. She critically described Getman's developmental vision training program, which assumed a causal relationship between visual performance and learning. The theories of reading readiness and developmental programs were reviewed, as were several experimental studies that had severe methodological faults. She concluded that there was virtually no definite proof, and no real theory, to substantiate the claim that optometric vision training programs helped children with learning disabilities.

A review by Pierce (1977) stressed the need to have proper control groups and pointed out the weaknesses inherent in many studies. The fact that the following statement had to be made is a sad reflection on much of the literature: "Treatment of binocular function in patients without any binocular problems is not likely to produce any significant effects". He concluded that vision training, particularly of vergence ranges, can result in greater reading speed. He noted that kinds of perceptual motor training that are most effective and which children will be helped by them still has to be established. He felt that conceptual style and conceptual strategies may be the common factor in many successful perceptual-motor training programs. Many of the references in this review were not published in refereed journals and, although the general methodological requirements of research were highlighted, the degree to which the papers under review met these requirements was not generally noted.

Seiderman (1980) studied 36 learning disabled children who were experiencing visual and/or perceptual difficulties. They were divided into 2 groups that were matched for age, sex, IQ, severity of visual and perceptual difficulty, and degree of reading deficit. The experimental group received intensive individually prescribed vision therapy consisting of perceptual and visual training; full details were not given. The control group participated in physical education, art, or science classes for an equal period of time; the placebo treatment was not individually structured and may, therefore, have had less of a Hawthorne effect than the experimental treatment. The experimental group showed a statistically significant improvement in vergence amplitude, reading performance, and some perceptual tasks. The author concluded that visual training could help learning disabled children with deficits in binocular co-ordination and processing skills to respond more effectively to reading instruction.

Metzger and Werner's (1984) review concentrated on papers that were critical of visual training and seemed to be based on the assumption that RD is an homogeneous condition.

The authors described "structural vision" as referring to the ocular characteristics of the visual system, such as refractive capability and ocular motility. "Functional vision", on the other hand, referred to visual perception and included measures of discrimination and recognition. The main assumption of visual training, that visual problems cause or contribute to RD, was criticised on the following grounds: inadequate screening tests, inadequate normative data, and lack of data from perceptual testing. The types of visual training and its efficacy in some studies were briefly reviewed. The results of some visual perceptual studies were used to suggest that perception was not a determining factor in RD; the problem was thought to lie in accessing the portions of memory that relate to verbal information. The authors concluded that ocular factors were virtually irrelevant in RD.

Levine (1984) pointed out that the co-existence of erratic eye movements and RD in a child need not comprise an aetiologic interaction. He criticised visual training and the methodology of some research projects, particularly the error of assuming a homogeneous aetiology of dyslexia. He summarised thus: "the wholesale endorsement of single explanations and treatments for large numbers of children with clinical disorders as complex as RD deserves our outspoken mistrust."

Solan (1985) described 3 case studies who were all said to have slightly above-average general scholastic performance, average reading ability, and deficient eye movements whilst reading; very little psychometric data were given to support these descriptions. The subjects demonstrated convergence insufficiency, poor binocular fusion, "sluggish" accommodation, and their eye movement pattern whilst reading was said to be comparable with that of much younger children. They were given between 10 and 18 sessions of vision training aimed at improving: the quality and ranges of binocular fusion and their reading eye movements. After treatment the reading performance, eye movement pattern, and binocular fusion had improved; and there was less asthenopia during reading. It was concluded that the subjects had been using compensatory strategies to partially overcome their oculomotor problems before treatment. Unfortunately, the subjects were also given individual reading instruction, and they were "selected because they represented clear-cut examples".

Beauchamp (1986) described optometric vision training included the following: prescribing low power corrective lenses; training ocular movements; manipulating accommodation; and other activities such as training body movements, exercises, diet, perceptual training, and extra teaching. He pointed out that the wide range of techniques made scientific evaluation more difficult. Perceptual motor training was criticised as ineffective and he believed that poor tracking (saccadic eye movements) in reading were the result, rather than the cause, of poor cognition. He concluded that more (rigorous) research was needed and that it would be more profitable to concentrate resources on teaching programs for RD children. The author, who was chairman of the Committee on Vision and Learning Disabilities of the American Academy of Ophthalmology, stated that because few ophthalmologists engaged in "vision training" they had no vested interest. Whilst this makes an important point about some practitioners' financial incentive in advocating this therapy, the fierce commercial competition between ophthalmologists and optometrists as providers of primary eyecare in the USA means that neither party is likely to maintain an objective perspective.

Helveston (1987) criticised studies that are often used to support "perceptual training" for not adhering to standard scientific methods of evaluation. Christenson et al. (1990) noted that some authorities mistakenly associate standard optometric vision therapy with controversial and unfounded treatment regimens. They described dysnemkinesia as a subgroup of dyslexia that was particularly "environmentally influenced" and can usually be modified with therapy to enhance visual-motor and visual perceptual skills. This paper was criticised in Section 1.6.

Cohen et al. (1988) reviewed over 200 papers on the efficacy of optometric vision therapy; this was said to be synonymous with vision training, orthoptics, eye training, and eye exercises. They concluded that vision therapy was an effective therapeutic modality in the treatment of many physiological and information processing dysfunctions of the visual system, including oculomotor problems associated with RD. This review did not adopt a critical stance and cited many papers that were published in non-refereed or loosely refereed journals.

Rounds et al. (1991) believed that the majority of RD individuals have deficiences in some "basic visual skills" and that within the population of college students there is a RD group with normal IQs. They selected 19 such students, using vague selection criteria and without any assessment of intelligence, and measured their eye movements whilst reading text, which was inappropriately set at a normal college level. Half the students were randomly selected and given "oculomotor skill enhancement visual training"; this seemed to consist of sessions when the subjects practised pursuit or saccadic eye movements. Several eye movements parameters had significantly improved after treatment in the experimental relative to the control group. The lack of a placebo treatment for the control group make these results difficult to interpret.

2.6.3 Conclusions

More (rigorous) research is needed, particularly using matched control groups and placebo treatments. It is concluded from the available evidence that vision training to specifically treat an oculomotor anomaly that has been identified in a dyslexic individual can alleviate this problem and that this may in turn ease symptoms of asthenopia when reading.

2.7 VISUAL PROCESSING

This review will concentrate on studies that have investigated lower-level aspects of visual processing. Hoffman (1980) found that learning disabled children performed poorly on a battery of "visual-perceptual motor tests"; the weaknesses of this study were described in Section 2.4. Kaplan (1983), in a study that is described in more detail in Section 4.3, found smaller form visual fields, measured in a monocular campimeter, in a RD than in a control group. This anomaly was said to be successfully treated with coloured light stimulation (syntonics).

Geiger and Lettvin (1987) investigated the relationship between the drop in peripheral V/A with increasing retinal eccentricity and the lateral masking effect. This latter effect seems to be analogous to the crowding effect (*see* Section 2.3.1) and depends on the retinal eccentricity and the distance between the letters. The subjects were 5 adult normal readers and 5 adults who were receiving reading remediation. These small groups were not matched for age or intelligence, no psychometric data were given, and the description of "dyslexic" for the experimental group seems, from the available information, to be inappropriate. In the first experiment 2 letters were presented, one centrally and one at varying peripheral eccentricities; the subjects' task was to correctly identify the peripheral letter. Exposure times were less than 8 ms and were adjusted so that correct identification did not quite reach 100% at any eccentricity; this may have created a confounding variable. The dyslexic group were significantly worse than the control group at identifying letters when they were within 5° of fixation, but were significantly better when they were between 5° and 12.5° from fixation. Geiger and Lettvin's (1987) second experiment found that the effect of lateral masking was significantly greater in the dyslexic group near fixation, but had significantly less effect in this group at an eccentricity of 10°. They concluded that dyslexic children learnt to read outside the foveal field and briefly described a case study of a "severe dyslexic" who complained of "scrambled" letters. His reading performance was said to improve with a mask that encouraged peripheral viewing; it is not clear why this should help and the placebo effect was not considered.

Dunn (1987) pointed out some design problems in Geiger and Lettvin's (1987) study that he thought were of sufficient magnitude to prevent meaningful interpretation of the data presented. Helveston (1987), similarly, felt that the conclusions of Geiger and Lettvin (1987) were totally unsupported by their data.

Solan et al. (1990) investigated the increase in VEP amplitude with binocular compared with monocular viewing: the "binocular advantage". They noted that the literature suggested that intersensory integration played a role in reading and hypothesised, controversially, that binocular vision is a form of intersensory integration and may, therefore, be deficient in dyslexia. Their experimental group of 14 children, although persistent poor readers, only read slightly below expectation. Monocular and binocular single channel VEPs were recorded for 2 different check sizes and the maximum VEP amplitudes were calculated. The control children exhibited significantly larger monocular and binocular overall amplitudes, although the interactions between group and viewing condition (monocular or binocular), check size, and contrast reversal rate were not significant. The authors concluded from a t-test that the greater binocular advantage in the control group approached significance ($p < 0.05$). The value for "t" that they gave (-2.03), however, in fact suggests that this was an overestimation ($0.05 < p < 0.10$). In any event, their ANOVA ("learning x viewing interaction") did not reach significance ($p = 0.356$). Solan et al. (1990) concluded that the visual processing of the 2 groups was different. They believed that disparities between the age and IQ of the groups were irrelevant because they were unlikely to influence the VEP; the potential confounding variable of attention was not considered.

Geiger and Lettvin (1991) reported similar data to Geiger and Lettvin (1987) that were interpreted as a lateral masking or crowding effect. This was greater in the direction of reading: to the right in English-speakers and to the left in a sample of Hebrew-speaking individuals. They suggested that their results were linked to sequential problems and represented an inadequacy in preparing the scene for cognition. Treatment, with their masking device, was said to train a new visual strategy that enhanced the ability to read.

2.7.1 Research on a Transient System Deficit

2.7.1.1 Parallel Visual Pathways

Retinal ganglion cells can be categorised into separate classes by a number of different anatomical, physiological, or psychophysical criteria. Although there can be some overlap in the functional characteristics of the pathways and a "mixing" of the pathways in higher visual centres, parallel pathways, or channels, of visual processing exist throughout the visual system (Bassi and Lehmkuhle, 1990).

Anatomical studies of ganglion cells in cats have led to the classification of pathways as "X", "Y", and later "W" (Crawford et al., 1990). For primates, there are differences in opinion regarding the homology of X and Y cells (Lennie et al., 1990). Ganglion cells, however, that project to the magnocellular layers of the dorsal lateral geniculate nucleus (M-cells) seem broadly analogous to the Y pathway, and ganglion cells that project to the parvocellular layers of the geniculate (P-cells) seem broadly analogous to the X pathway (Lennie et al., 1990). The M- and P-cells project to different layers of the visual cortex (Hubel, 1988, p. 104) and the former pathway continues to the parietal and the latter to the temporal visual association areas (Ungerleider and Mishkin, 1982; Mishkin et al., 1983).

Cells in these 2 pathways exhibit different physiological responses to various stimuli (Kaplan et al., 1991). The M-cell pathway responds quickly to low to middle spatial frequencies modulated at higher temporal rates, whereas the P-cell pathway responds more slowly to high spatial frequencies modulated at slower rates (Zeki and Shipp, 1988). The former pathway has therefore been described as having a transient response, and the latter as having a sustained response (Gilchrist, 1988). Hockfield et al. (1990) used molecular markers to demonstrate the similarity between human and monkey cortical organisation and provide further evidence for the existence of parallel visual pathways in the human brain.

2.7.1.2 Properties of The Transient and Sustained Systems

The spatial contrast sensitivity for drifting gratings demonstrates a loss of sensitivity at high spatial frequencies and an increase at low (Gilchrist, 1988). Kulikowski and Tolhurst (1973) measured the contrast sensitivity for stationary flickering gratings and found 2 distinct thresholds. At one contrast level, the flicker became noticeable while at another the spatial pattern appeared. These 2 thresholds vary independently with changes of spatial or temporal frequency, suggesting that each is the response of a separate processing channel. The flicker sensitive channel responds best to rapid temporal changes, and has been identified with the transient pathway; the other responds best to stationary or slowly changing stimuli and has been identified as the sustained channel (Green, 1981).

Psychophysical evidence, therefore, has provided perceptual correlates of the physiological and anatomical classifications. The characteristics of these channels are summarised in Table 2.5.

property	sustained	transient
ganglion cells	P-cells	M-cells
layer of LGN	parvocellular	magnocellular
ultimate cortical destination	temporal	parietal
response property	long	short
temporal conditions for maximum response	static targets/low frequency flicker	moving targets/high frequency flicker
spatial conditions for maximum response	high spatial frequencies	low spatial frequencies
receptor field size	small	large
retinal location	more central	more peripheral
sensitive to blur	yes	no
persistence of response	throughout stimulus	at onset/offset of stimulus

Table 2.5 Characteristics of sustained and transient channels.

2.7.1.3 Dyslexia: a New Look at The "No Visual Deficit" Hypothesis

There is considerable evidence to suggest that disabled readers frequently have various forms of language deficiency (Hulme ,1981, pp. 52-53; Sherman et al., 1989) and this has led to the "no visual deficit hypothesis" of RD. This hypothesis has been exemplified by the work of Vellutino (e.g., Vellutino 1987), which also draws upon methodological weaknesses in much of the research that supports a visual deficit (Vellutino et al., 1977). The no visual deficit hypothesis is also supported by the unsuccessful application of visual perceptual therapy in the remediation of RD (Hammill, 1972). The lack of a distinct pattern in the literature on optometric correlates of dyslexia (*see* Chapters 2-4) may provide further evidence for the no visual deficit hypothesis.

It has recently been suggested (e.g., Lovegrove et al., 1990), however, that previous investigations failed to find a visual deficit because the wrong type of deficit was being searched for. There is now considerable evidence to suggest that, in up to 70% of cases of dyslexia, there is a deficit of the transient visual system. If this is the case, then it is not surprising that previous research relating to visual problems that are likely to be mediated through the sustained visual system (e.g., V/A) failed to find such deficits in dyslexic populations.

Hulme (1981, p. 30), before a transient system deficit in dyslexia was hypothesised, concluded from a review of tests of visual memory in RD that this condition was associated with "some general immaturity of brain function which hampers the processing of very rapid stimuli". The theoretical and experimental evidence for a defect of the transient visual system in specific RD has been the subject of an extremely thorough review by Lovegrove et al. (1986a). More recent reviews (Lovegrove et al., 1990; Lovegrove, 1991a,b,c) have provided briefer summaries of the evidence. A detailed analysis of the subject can be found in these papers; the most important points will be summarised here. Further details of individual papers that relate to the present research will be described in greater detail in the appropriate sections. Before considering the evidence for a transient system deficit in dyslexia, the role of this system in reading will be considered.

2.7.1.4 Transient and Sustained Sub-System Interaction During Reading

The role of the transient and sustained sub-systems during the reading process has been considered by Breitmeyer (e.g., Breitmeyer, 1980, 1983), and his work has been reviewed by Lovegrove et al. (1986a). Figure 2.2 illustrates the hypothesised interaction between these systems during 3 successive fixations whilst reading; inhibition is an essential part of this theory.

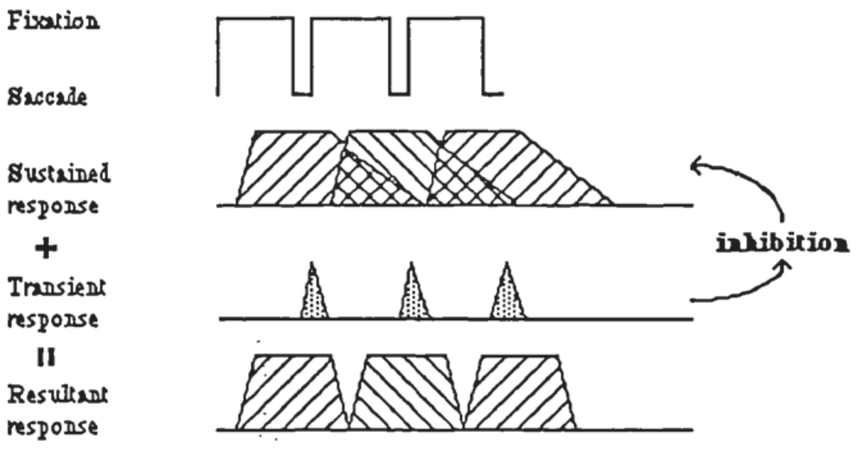

Figure 2.2 The hypothesised interaction of the transient and sustained sub-systems during 3 successive fixations whilst reading. The top trace schematically represents the eye movements, characterised by saccades and fixation pauses. The hypothesised sustained response is given on the next trace, which is thought to be inhibited by the transient response (third trace) to give the resultant response, on the bottom line. (Adapted from Breitmeyer, 1980).

The image formation during a fixation is thought to be mediated through the sustained visual pathway. The characteristics of this system mean that the response may only fade slowly after the fixation has ended, so that the image could persist into the next fixation (this is a form of visible persistence). A superimposition of subsequent images is thought to be prevented by inhibition from the transient visual system which is stimulated during a saccade by the movement of the visual image across the retina. If this theory is correct, then the interaction of the transient and sustained sub-systems is important for normal reading.

One method that is used to investigate the interaction between the transient and sustained systems is where the visibility of a briefly displayed target pattern is reduced by a briefly displayed masking pattern. The types of "masking" techniques and their use in studies of the transient and sustained channels has been extensively reviewed by Breitmeyer and Ganz (1976). These studies provide circumstantial evidence for the above model of the role of the transient and sustained systems in reading (Breitmeyer and Ganz, 1976); the validity of this model has not been directly tested. One recent study (Macknik et al., 1991), however, supported the notion that saccadic suppression is mediated by the transient visual system.

2.7.1.5 Spatial Frequency Analysis and Specific RD

Lovegrove et al. (1986a) used 4 measures of spatial frequency analysis to provide evidence of a transient system deficit in dyslexia. Firstly, they looked at visible persistence and spatial frequency processing. An early review (Hulme, 1981, p. 26) concluded that longer iconic persistence is a correlate or reading retardation. Lovegrove et al. (1986a) explained the types of visible persistence, and noted that this variable increases with increasing spatial frequency (Breitmeyer et al., 1981), possibly owing to transient-on-sustained inhibition (Bowling et al., 1979). Badcock and Lovegrove (1981) showed that this effect was reduced in reading retardates, who also demonstrated an atypical relationship between contrast and visible persistence. These findings were explained in terms of tranient-on-sustained inhibition, and this hypothesis had been investigated further by studies employing visual masking techniques. These confirmed that RD and control groups differed in terms of their spatio-temporal processing; this was explained as a transient system deficit in dyslexia, probably of cortical origin.

Secondly, Lovegrove et al. (1986a) reviewed their work based on the spatial contrast sensitivity function (*see* Section 7.4.8.1). This function may be considered as the envelope of activity of several narrow-band spatial frequency channels and is influenced by stimulus duration, field size, and mean luminance. The CSF of children with a specific RD demonstrated decreased sensitivity at low spatial frequencies and similar or possibly increased sensitivity at high spatial frequencies (Lovegrove et al., 1982). These findings, which were not influenced by field size, were interpreted as a defect of the transient visual system; this was supported by studies using masking techniques (Martin and Lovegrove, 1988).

The third method of spatial frequency analysis that Lovegrove et al. (1986a) discussed related to flicker contrast sensitivity (*see* Section 7.4.8.2). Flicker thresholds may be a measure of transient system function and RD children had been found to have reduced contrast sensitivity to flickering stimuli. One experiment found that the differences between the groups was greatest for high spatial frequencies (Martin and Lovegrove, 1987); this seemingly paradoxical finding was explained in terms of a defective transient system being inhibited to a greater degree by the sustained system.

Fourthly, Lovegrove et al. (1986a) described their studies that had investigated spatial tuning. Spatial tuning is thought to be mediated through the sustained system, and they found no differences between RD and control children in these studies.

2.7.1.6 The Role of a Transient Visual System Deficit in Dyslexia

The perceptual consequences of a transient system deficit in RD children have been studied by Williams and co-workers; their work was reviewed by Williams and LeCluyse (1990), and only the main points will be summarised here. Williams and Bologna (1985) associated the transient system with perceptual grouping. They found deficient perceptual grouping in poor readers and suggested that this may represent an early, pre-attentive, visual processing deficit. This study, however, suffered from several methodological weaknesses. It was later shown that disabled readers had "sluggish" foveal temporal processing (Williams et al., 1989) and peripheral visual processing that is characterised by a lack of inhibitory processes (Williams et al., 1990) compared with normal readers. Williams and LeCluyse (1990) interpreted these findings in terms of a transient system deficit and discussed their consequences for reading performance.

Williams et al. (1987), using a search task, found that image blurring seemed to re-establish the normal pattern of visual processing in disabled readers, supposedly through re-establishing the temporal precedence of the transient system. This study, however, used small subject numbers, gave very few details of subject selection criteria, and might be better explained by the blurring removing the high spatial frequencies from, and hence weakening, the sustained image. This would aid saccadic suppression, which may be impaired by a transient system deficit. Williams (1991a) hypothesised that colour, like blurring, could be used to re-establish the temporal precedence of the transient visual system in dyslexia. She found some evidence to support this hypothesis (*see* Section 4.4.4.4).

May et al. (1988) found that poor readers have a deficit in visual temporal order judgements, resulting in a delay in detecting the temporal ordering of events. They suggested that a transient system deficit may represent the initial flaw that results in poor temporal order judgements. They further hypothesised that transient subsystems may not be limited to the visual system. Subtle, but ubiquitous, problems in transient subsystems in all the senses and the motor system could, therefore, lead to the myriad of sensory, motor, perceptual, and cognitive deficiences that have been observed in the RD. They also described the antithesis: that the basic sensory system responsible for precise timing in the visual (or any other) system only develops at a normal rate with appropriate environmental stimulation. Reading, therefore, may represent "exercise" that the transient system needs to help it develop. The latter explanation would seem unlikely since reading is not a "natural" task (see Section 1.1). The authors' theories rest on the controversial assumption that there is a fundamental sensory system responsible for precise timing.

There have been several attempts in the past to classify dyslexia into 2 sub-groups, one with a visuo-spatial deficit and the other with a language deficit (Doehring et al., 1981, pp. 36-40). Lovegrove et al. (1986a) argued that the visual disabilities shown by the former sub-group do not reflect low-level visual processes of the type characterised by his research on a transient system deficit. This argument is supported by the finding of a high correlation between an inability to read nonsense words and poor flicker sensitivity; this may suggest that poor phonological coding is linked to a transient system deficit (Lovegrove, 1991a).

Lovegrove et al. (1986a) subjected the combined results of their visual persistence experiments to discriminant analysis. This placed 75.4% of the RD group in a "visual deficit" group, whilst only 8% of controls fell into this category. Lovegrove et al. (1986a) acknowledged that the presence of a transient system deficit as a correlate of dyslexia does not prove a causal link. However, they did suggest mechanisms for such a link, both through prolonged visual persistence causing a superimposition of subsequent images, and by defective global saccadic programming. More work is needed in this area, but there is now experimental evidence showing that the transient deficit does not result from failure to learn to read (Lovegrove et al, 1986b), and one case study may suggest that treatment strategies could be based upon these models (Geiger and Lettvin, 1987).

Hill and Lovegrove (1991) noted that the transient system probably processed the textual information surrounding a fixated word. They hypothesised, therefore, that the reading performance of subjects with a specific RD could be improved by removing peripheral information. Their first and second experiments compared 10 RD with 5 control and 12 RD with 12 control children, respectively. In the first experiment the groups were approximately matched for age but the normal readers had a higher IQ; in the second experiment the groups were matched for IQ but the controls were, on average, 17 months older. Transient function was measured by sensitivity to 20 Hz flicker of 0.3 and 6 c/°

stimuli. The children read text that was presented under 3 conditions: one word at a time in the centre of a screen, one word at a time moving across the screen, and with a whole line presented at a time. In both experiments the RD groups performed similarly to the controls in the first 2 conditions, but were worse than the controls in the last condition. The authors concluded that the transient deficit impaired the integration of peripheral information within a saccade, but did not influence the persistence of information across saccades. There was a positive relationship between one word advantage and flicker sensitivity in experiment 1 but not in experiment 2. They attributed this to a lower illumination level in experiment 1, although the luminance level in experiment 2 was closest to that of a normal page of print. The authors cautioned against concluding that a visual deficit in dyslexia could be solved by presenting one word at a time; their results could be explained, alternatively, by eye movement or attentional deficits.

Bear (1987) briefly outlined a theory based on the proposition that the sustained system was expanded and specialised within the left temporal lobe, projecting to the association cortex that mediates language, whilst the transient system may have become dominant within the right hemisphere accounting for that hemisphere's relative superiority in aspects of spatial construction and attention. He linked this to findings of cortical anomalies in dyslexia (see Section 1.5.3.1) to suggest that dyslexia could result from a congenital abnormality of the sustained system. He used the findings of Geiger and Lettvin (1987) to support his theory, but did not relate this to the research on a transient system deficit, nor to the evidence for unimpaired V/A in dyslexia.

Stein (1991a) noted that information about the rate and direction of movements of images across the retina are projected via the magnocellular pathway to the posterior parietal cortex (PPC), where he believed the association of retinal and eye movement signals occurs. He suggested that this links the transient system deficit in dyslexia with unstable binocular control, poor stereoacuity, and inaccurate judgements of visual direction.

May et al. (1991) investigated the visual evoked potentials (VEPs) obtained with sinusoidal grating stimuli of 15% contrast presented for 200 ms in good and poor readers. The onset responses were not significantly different between the groups, although some aspects of the offset responses were significantly different. The authors noted that the differences were small and probably did not constitute a clinically relevant finding, but they went on to relate their finding to a transient system deficit in the poor readers.

Livingstone et al. (1991) recorded visually evoked scalp potentials of 5 dyslexic and 7 control adults who were matched for age, intelligence, and professional level. The dyslexic subjects showed diminished evoked potentials for rapid, low contrast, stimuli but normal responses to slow or high contrast stimuli. They suggested that these findings were evidence of an abnormality in the magnocellular pathway at the level of the striate cortex or earlier. The authors noted that dyslexic children often do poorly in tests of rapid auditory transitions and hypothesised that other sensory and motor systems were similarly divided into fast and slow subdivisions and that dyslexic individuals were specifically impaired in the fast subdivisions. This study only used one channel and, since variability may increase as contrast decreases (Thompson, 1991), replication with more subjects is required to validate these results.

Breitmeyer (1991) reported a study by Galaburda and Livingstone (in press) that had examined, by autopsy, the lateral geniculate body in a small number of dyslexic and control individuals. They found unusually small cell sizes in the magnocellular layers of the dyslexic group compared with controls: the parvocellular layers had similar cell sizes in both groups. It should be noted, however, that analogous anatomical observations resulting from deprivation experiments occurred without a physiological correlate (Hubel, 1988, p. 208).

2.7.1.7 Weaknesses of the Research on Parallel Processing in Dyslexia

Experiments directly relating the functions attributed to the magno- and parvo-cellular pathways to the transient/sustained systems have only been carried out on primates. The transient/sustained distinction is likely to be an oversimplification, according to the most recent and authoritative reviews of primate physiology (Kaplan et al., 1991) and human psychophysics (Wilson et al., 1990). Despite the need for further work, it can be seen that this distinction has provided a useful organising hypothesis in the study of RD. Although we cannot ultimately prove the truth of this model (Gilchrist, 1988), it has thus far withstood investigation reasonably well and its usefulness as an organising tool in dyslexia seems to warrant its continued use at the present time (Williams et al., 1990).

Most of the research in this area has used subject groups that are of a relatively small size. For example, Williams et al. (1989) compared 4 children who were disabled readers with 4 who were good readers and 4 adults; and Lovegrove et al. (1982, experiment 1) compared 2 groups of 5 boys. The tendency, particularly of Lovegrove's team, to carry out broadly similar experiments using different subject groups (e.g., Bowling et al., 1979) partly negates this criticism, but in a disorder with a supposed heterogeneous aetiology (Singleton, 1987) it may be advisable to use larger subject groups.

Considering that several different paradigms have been used to demonstrate a transient system deficit in dyslexia, it is surprising that the external consistency of these tests has not been investigated by applying more than one of these procedures to the same subjects. Such a study could also include a test of sustained function; if a dyslexic group were found to perform worse than a control group on more than 1 test of the transient system but to perform similarly in a test of sustained function this would provide considerable support for the transient deficit hypothesis. Similarly, it has not yet been shown that the higher level "perceptual consequences of a transient deficit" (e.g., Williams et al. 1990) do actually occur in the same children as manifest the lower level deficit identified by Lovegrove's team.

The level of illuminance in experiments that have demonstrated a transient system deficit in dyslexia seems to be critical, with low levels of illuminance enhancing the significance of the results (Cornelissen, 1991; Lovegrove, 1991b; Hill and Lovegrove, 1991). The reason for this appears to be unclear at the present time.

Breitmeyer (1983) noted that the implications of prolonged visual persistence in specific reading retardation depends on whether or not the strength of saccadic suppression (transient-on-sustained inhibition) is more or less equal in RD and normal readers. Some of the paradigms used by workers in this area involve difficult judgements for their subjects (Burbeck, 1981) and it is possible that inter-group differences are due to criterion differences. This criticism particularly applies to tests of visual persistence where the subject is often asked to "ignore flicker" or to "report whether a distinct blank interval appeared" (Bowling et al., 1979). Georgeson and Georgeson (1985) showed this method to be unreliable and stated that:

> "there is no compelling evidence that the method measures visible persistence. Because the criterion problem is so severe, effects of stimulus variables or differences between groups of subjects may be due as much to criterion shifts as to genuine changes in visual performance. We therefore urge great caution in the use and interpretation of this method."

The transient and sustained systems have been described as the "movement detector" and "pattern detector" respectively (Gilchrist, 1988), although it seems likely that both systems can signal motion (Green, 1981). Parallel processing is thought to be a common feature of vertebrate visual systems (Crawford et al., 1990) and is likely to be a fundamental adaptation to speed visual processing (Lennie et al., 1990). It therefore seems unlikely that a defect of this system would only impair reading. In this context, the presence of a subtle transient deficit that is a non-causal correlate of dyslexia seems more likely than a transient deficit playing a major causal role.

Hulme (1988) questioned whether a deficit of the transient system provides a likely explanation for reading problems. He cited evidence suggesting that retarded readers do not find it easier to read isolated words than prose, and noted that the reading difficulties were characterised by an inability to master the phonic aspects of reading. He accepted that the deficits found by Lovegrove's team were correlates of dyslexia but thought that they were far less likely to be causally related to the RD than other correlates, such as poor verbal skills. He finally pointed out that dyslexic children performed similarly to controls on visual memory tasks.

May et al. (1990) investigated the features of natural images that influenced their visual persistence. Their findings suggested that earlier results with sinusoidal gratings may not predict how complex, aperiodic, images might be processed temporally. These seemed to be influenced by the spatial frequency and contrast of local features within the image. Grigsby et al. (1991) noted that colour vision was mediated through the parvocellular channel and that chromatic properties were important for analysing visual disorders in terms of selective losses in parallel pathways. This approach does not seem to have been used in dyslexia research.

Müller and Groner (1991) investigated Swiss dyslexic and control children using a measure of visible persistence, a motion perception task, and a subthreshold summation "line spread function". There were no significant differences between the groups. The authors cautioned that: their dyslexic sample consisted of 7 children with mild RDs and their paradigm did not directly replicate that of any other workers. It also seemed that their groups were not matched for intelligence.

Kruk and Willows (1991) described 3 experiments, involving gradual approximations toward more reading-like situations, that assessed how visual processing differences between normal and disabled readers might be manifested. The experiments involved visual form discrimination in a backward masking paradigm. Stimulus onset asynchrony was varied to provide a measure of visual persistence. The results showed significant differences in accuracy between the normal and disabled readers across all experiments, but few overall differences in response times. The authors concluded that the transient system deficit may not provide a complete account for the effects obtained. This seems to be a more appropriate conclusion than their additional comment that visual processing differences between the groups can manifest themselves within the context of "natural" reading.

2.7.2 Conclusions

There is now reasonably convincing evidence suggesting a visual processing deficit in dyslexia. This deficit seems to specifically impair channels that process low spatial and high temporal frequencies.

2.8 General Conclusions

2.8.1 Summary

The literature suggests that V/A is not a strong correlate of dyslexia, although more research investigating near V/A is required. Refractive error, similarly, does not appear to be a strong correlate of dyslexia, although hypermetropia may be linked to RD. Poor convergence and low fusional reserves (prism vergences) seem to be more common in dyslexia, as are exophoria and accommodative dysfunction. Abnormalities of reading eye movements have been found in dyslexia, although the research on non-reading eye movements equivocally suggests that this may be the result rather than the cause of the RD. The research that has been used to support the existence of a cerebellar-vestibular dysfunction in dyslexia is unconvincing. There is some evidence that visual training can help dyslexic children with oculomotor anomalies, although this is controversial. Finally, there is reasonably convincing evidence for a visual processing deficit in dyslexia, which seems to selectively impair transient processing.

2.8.2 Observations on Methodology

The import of many studies in the literature has been severely reduced by methodological deficiencies. These can be summarised as follows:

1. A control group matched for age, sex, and intelligence should be included.
2. Subjects should be unselected, or at least should not have primarily consulted an eyecare practitioner; such patients are more likely to demonstrate visual problems.
3. If RD subjects are defined by their school grade it should be borne in mind that they may have repeated years in their earlier schooling; hence, grade-matched groups may not be age-matched (Dunlop and Banks, 1974).
4. Optometric parameters should, wherever possible, be treated as continuous variables and should avoid artificial test ceilings.
5. It should not be assumed that optometric variables conform to a Gaussian distribution, particularly in view of questions concerning the psychophysical scaling of many of these parameters (Pierce, 1977).
6. The potential confounding variables of attentional difficulties and hyperactivity should be considered, particularly in studies that analyse eye movement

characteristics (Garzia et al., 1990). This may be related to the effect of cognitive demand on the accommodative and vergence systems (*see* Section 9.2.1).

2.8.3 Causality

The presence of optometric correlates of dyslexia does not necessarily imply a causal link. Knehr (1941) described oculomotor functions, "ocular defects", and visual fields as "peripheral factors", in distinction from the "central factors" in reading such as familiarity with words, ideas, and meanings. This distinction is similar to that between "lower level" visual functions, including visual processing in the striate cortex, and the "higher level" linguistic processing skills that are required for reading. A causal relationship can be investigated by using an intervention or treatment, although most research that has used this technique has served to heighten the debate rather than resolve it (*see* Section 2.6.2 and 3.3). Limited information on this relationship can also be obtained by finding whether the visual deficit precedes the development of reading.

Another way of investigating whether associated factors are causally related to the RD is to study performance at a simulated reading task that does not require the same high level processing skills as reading. To help differentiate the more peripheral problems of visual processing from higher linguistic problems, such a test should have a minimal linguistic content. The need for such a test was pointed out as early as 1943 by Hyslop (in the discussion appended to Orton , 1943):

> "in examining children who are presumed to have defective vision because they do not read, one may note disorders of integration through studying how they use their eyes and understand the meaning of objects which are similar in size but do not involve the language function."

CHAPTER 3

A REVIEW OF THEORIES RELATING DYSLEXIA TO CEREBRAL AND OCULAR DOMINANCE

3.1 Reviews and Theories

3.1.1 An Overview of General Theories on Ocular Dominance

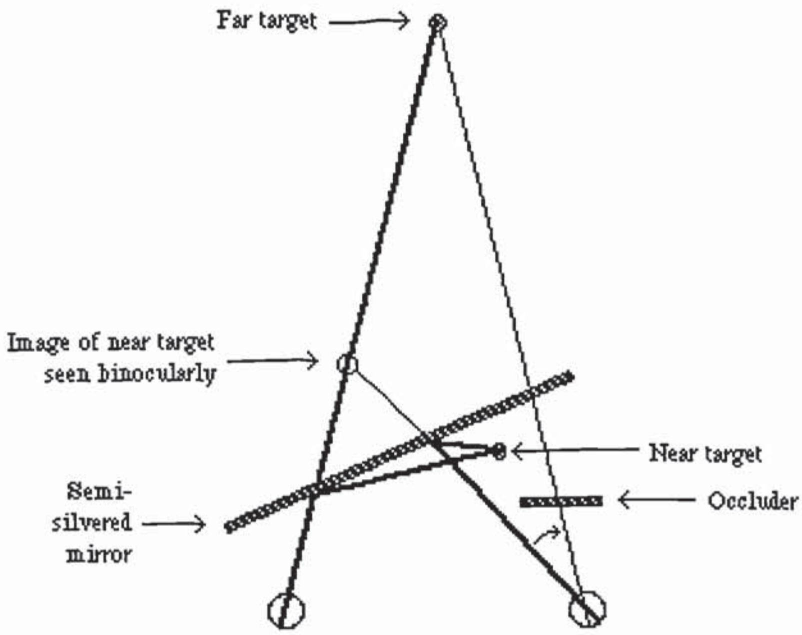

Figure 3.1 An illustration of Hering's experiment (*see* text for explanation). After Ogle (1962).

Ogle (1962) listed several criteria that had been suggested to assess ocular dominance, none of which had proved reliable. He considered that ocular dominance was basically dependent upon sensory phenomena, but that there was also a motor aspect. This was best demonstrated by the following experiment, which was attributed to Hering. In a dark room a subject fixated binocularly the image of a small illuminated near target seen by reflection from a semi-silvered mirror (*see* Figure 3.1). An occluder prevented the right eye from seeing a second target, which was placed in the distance in line with the left eye. Initially, only the near target was illuminated and both eyes were converged on this. The near target was then extinguished and the distance target simultaneously illuminated. The left eye fixated the far target without movement and the right eye (although occluded) diverged as though to fixate the distant target. The hypothesis was that if the right eye was dominant the far target would appear to move to the right, i.e., the subjective direction of the image of the far target was influenced by the movement of the right eye, which did not see it. If the right eye was non-dominant, then no movement of the far target was apparent. The apparatus could be reversed to make the right eye fixate both the near and the far targets. In mixed dominance the target appeared to move with either eye fixating. A heterophoria changed the magnitude of the apparent movement.

Ogle (1962) believed that the eye in which a fixation disparity occurred was also a measure of motor ocular dominance. He described an experiment to assess this and reported some preliminary results showing concordance between these 2 techniques. He also suggested that in binocular retinal rivalry there was a greater tendency for the image of the non-dominant eye to be suppressed. He did not differentiate between this form of sensory dominance and motor dominance and seemed to consider that one eye was innately dominant for all tasks.

Mallett (1966) gave the following definition of ocular dominance:

> "The dominant eye is the one which less readily relinquishes binocular fixation or foveal vision when binocular vision is distressed - the embarrassment is either inherent, as in uncompensated heterophoria, or may be artificially induced (*equally*) to both eyes."

He advocated a method based on a fixation disparity test; the eye in which the fixation disparity occurred was the non-dominant eye. If a fixation disparity was not present naturally then it could be induced by adding equal prisms to both eyes. This test, unlike sighting tests, often gave a neutral result (*see* Sections 3.1.2 and 3.2.2). Mallett (1966) stated that the eye that diverged at the near point of convergence was probably the non-dominant eye, but that this test very rarely gives a neutral answer. He described a third method, based on stereoscope or polarised tests, in which the eye that suppressed most readily was the non-dominant eye. These clinical observations were not supported by experimental data.

Michaels (1972) reviewed theories and research on ocular dominance, particularly that relating to dyslexia. He concluded that the dominant eye was not related to the eye with better vision and that dominance may express itself only in terms of function: structure may be irrelevant. Cerebral dominance was briefly discussed and sighting dominance was classified as a type of motor dominance because "the fixational mechanism of one eye is compared to the other"; this was not explained or supported. The literature suggested that reversals by the RD had nothing to do with cerebral laterality and retinal rivalry was not thought to be influenced by sensory ocular dominance or cerebral laterality.

Gilchrist (1976) concluded that there are 3 types of dominance in the visual system, sensory, sighting, and motor. He believed that visual system dominance should not be thought of as being "ocular" or wholly cortical but that a total intrinsic dominance existed in the visual system that was the sum of a number of factors. The position of the visual egocentre, or binoculus, was thought likely to be a reflection of the total intrinsic dominance, or vice versa. He said that the binoculus may lie in the sighting eye in monocular vision but binocularly must represent a compromise between the 2 eyes. Sighting and sensory dominance were both thought to be influenced, when the eyes were at rest, by an intrinsic dominance in the afferent pathway and cortex, although he felt that sighting, unlike sensory, dominance was essentially a monocular phenomenon. These 2 should not necessarily be directly related to motor dominance, which would be influenced by factors in the efferent pathway. The author seems to have been the first to appreciate that sighting dominance involves the choice of one of the diplopic images of an object to be aligned with the other object seen in single binocular vision. He did not extend this theory, however, to its natural conclusion (*see* Section 3.1.2) and instead thought of sighting dominance as monocular and distinct from sensory dominance.

Collinge (1979) adopted Gilchrist's (1976) classification of sensory, sighting, and motor dominance but noted that motor dominance could be changed by altering the sensory input with neutral density filters. He investigated the relationship between sighting and motor dominance in 30 subjects who were visually normal (few details were given). Three conventional tests of sighting dominance were used. Motor dominance was determined by comparing the relative magnitude of apparently irrelevant movements made by the unaligned eye when changing fixation from a near to a distance object, with both objects being aligned with the other eye. The movements were recorded objectively, and the eye that made the smaller "flick" movements was taken as the dominant eye. No statistical analysis was carried out but there was no absolute correlation between sighting and motor dominance, with 9 out of the 30 subjects having one eye sighting dominant and the other motor dominant. Collinge (1979) reviewed the neurophysiology of vision, including the distinction between the sustained ("what") cells and the transient and W ("where") cells (W cells are ganglion cells that project to the superior colliculus and are involved in the location of objects and the execution of eye movements). He suggested that motor dominance was mediated by the transient and W cells, and that sighting dominance was mediated by the sustained system; as the balance between the 2 visual sub-systems shifts so the dominance may alter. It is not clear whether he included sensory with sighting dominance under the control of the sustained system.

Humphriss (1982) showed that under binocular conditions a small amount of monocular blur (+0.50 to +0.75 D) immediately resulted in a small area of foveal suppression in the compromised eye. The binocular percept remained clear, although the para-foveal vision in the blurred eye was not affected. This phenomenon consistently occurred whether the dominant (presumably by sighting tests) or non-dominant eye was blurred, and if the blurring lens was rapidly moved from one eye to the other the foveal suppression alternated correspondingly.

Griffin (1982, p. 41) defined eye dominancy as the superiority of one eye over the other. Sighting tests were said assess motor dominancy, which could also be determined by NPC and fixation disparity tests. Sensory dominance could be assessed by retinal rivalry, colour fusion, and suppression.

Reading (1983, pp. 48-51) described binocular brightness matching, which had been used as a test of ocular dominance, and concluded that the visual system was capable of both summation and averaging of monocular brightnesses. The complex cells in the visual cortex respond binocularly: some 50% of the complex cells can be activated by shining a light in either eye (Reading, 1983, pp. 200-209). The binocular cells differ in the weighting given to stimulation from each eye; this represents a form of ocular dominance (Hubel, 1988, pp. 88-91). There is a fixed period of time, which starts at birth and is called the critical (Nelson, 1988) or sensitive (Reading, 1983, p. 208) period, when a degradation of the image from 1 eye will cause a shift of cortical ocular dominance towards the other eye; this is a result of competition between the 2 eyes for cortical access (Nelson, 1988).

Reading (1983, pp. 281-287) reviewed theories of ocular dominance, noting that visual dominance was more complicated than other forms of motor dominance. He modified Walls' (1951) classification of criteria for determining ocular dominance (*see* Table 3.1); it was pointed out that his group 2 dominances could be confounded by group 4 dominances.

Group 1: Sensory Dominances
1. The eye whose image is seen more frequently in binocular rivalry
2. The eye having better V/A
3. The eye that has the "more substantial-seeming image" in physiological diplopia
4. The eye whose afterimage persists longer
5. The eye whose image is less readily ignored, as in monocular microscopy
Group 2: Directional Dominances
1. The eye with which one sights
2. The eye with which the subject notices less jump in an alternate cover test
3. The eye whose occlusion elicits a greater feeling of uneasiness or unsteadiness, as in locomotion
4. The eye whose image undergoes less motion during changes in fixation from a far target to a near one
Group 3: Motor Dominances
1. The eye that fixates centrally in the presence of fixation disparity, heterophoria, or heterotropia
2. The eye that continues to fixate at distances within the near point of convergence
Group 4: Correlative Dominances
1. The eye before which one holds a card to read
2. The eye on the side of the dominant hand

Table 3.1 A classification of criteria of ocular dominances. Source: modified after Reading (1983, p. 284).

Reading (1983, pp. 281-287) thought that Hering's lateral-shift effect (*see* Figure 3.1 and accompanying explanation) may be the most useful means of classifying ocular dominance in terms of its significance in spatial vision. He said that the results of this test indicated that binocular localisations were organised around a point that can be located at one entrance pupil or the other, or any place in between. He thought, nevertheless, that the significance of its location was somewhat obscure.

Bennett and Rabbetts (1984, pp. 187-188) defined the dominant eye as the one that contributed most to the visual percept and listed several methods for determining this; all of these are included in Table 3.1 (group 1, number 5; group 2, numbers 1 and 4; group 3, numbers 1 and 2). They attached most significance to sighting tests and stated that some patients (e.g., anisometropes) have acquired a different ocular dominance for distance and near vision and that refractive corrections should, if possible, give the dominant eye the best acuity.

Mallett (1988) listed the following methods of assessing the dominant eye: (i) Sighting eye; (ii) the eye with better V/A; (iii) the eye that did not suppress on his polarised test (this involved reading small print, some letters of which were seen by each eye); (iv) the eye that maintained fixation just inside the near point of convergence; and (v) the eye in which a fixation disparity was not present . He preferred the last method; if a fixation disparity was not present this could be induced by placing prisms of equal power before each eye. He did not state whether he would anticipate similar results from all these tests and did not consider which assess sensory or motor dominance.

3.1.1.1 Conclusion

The literature suggests that the dominant eye varies with different tasks and that there are 3 basic types of dominance, sighting, sensory, and motor. The concordance between different tests that aim to specifically assess one of these types of ocular dominance has not been thoroughly investigated, but appears to be weak. This may suggest that these 3 basic groupings need to be further subdivided. The classification of sighting dominance as a basic category of ocular dominance may also be inappropriate. Some authors have classified this as a type of motor dominance, although the precise nature of sighting dominance does not appear to have been established.

3.1.2 Synthesis - a New Approach to Ocular Dominance

Most theories on ocular dominance have assumed that one eye is intrinsically dominant; it seems likely, however, that dominance changes with the task. This is illustrated schematically in Figure 3.2. Tests of ocular dominance that are bimodal (correlational), i.e., which are confounded by other systems of motor dominance such as handedness, are not included in this classification. Many tests of sighting dominance, such as "pointing tests", fall into this category

Tests of sensory dominance can be sub-divided into those that assess the dominant eye or hemi-field. Each of these sub-divisions can be classified further according to whether the tests interfere with normal viewing conditions ("unnatural") or do not ("natural"). For example, if a subject views polarised letters through the appropriate filter then this may detect the suppression of one eye, and the other eye will be the dominant eye under natural viewing conditions. Alternatively, if a subject is presented with dissimilar images in each eye so as to induce retinal rivalry then the eye whose image is present most often could be described as the dominant eye under unnatural viewing conditions. A similar distinction can be shown for tests that involve a motor component; if a subject has a fixation disparity then the eye in which this occurs in a well-illuminated polarised test with a good binocular lock is the non-dominant eye under natural viewing conditions. Unnatural tests of motor dominance can further be classified into those in which the eyes are fused, e.g., when a fixation disparity is induced by changing the vergence of the target; and those when eyes are dissociated, e.g., when the eye to break at the near point of convergence (NPC) or to misalign in measurements of fusional reserves is taken as the non-dominant eye. .

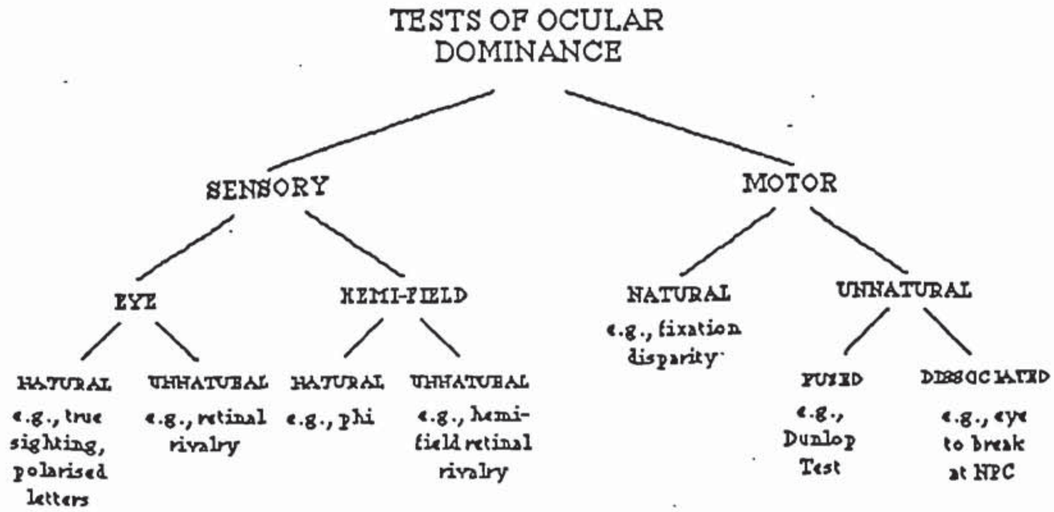

Figure 3.2 A schematic representation of the nature of various tests of ocular dominance. *See* text for explanation.

3.1.2.1 Sighting Dominance

Many tests of sighting dominance are confounded by other aspects of laterality, usually handedness (e.g., pointing tests). This problem could be partially overcome by using a test where, for example, a subject is asked to binocularly line up a circle drawn on a window with a spotlight in the distance. If he was told to move his head to bring the circle into alignment with the distance target, then if the head was moved to the left to bring the right eye into alignment then the right eye is the dominant eye, and vice versa. Even this test, however, may be confounded by a "general body laterality effect" that influences to which side a subject prefers to move his head.

During distance vision near objects, such as the circle on the window, can be seen in physiological diplopia. Subjects are not, however, normally aware of this diplopia; patients have to be taught to appreciate physiological diplopia before this phenomenon can be used for orthoptic exercises (Pickwell, 1989, pp. 72-73). The human mind ignores objects in the visual field that are not of interest; this will be called repression, since it seems likely that it represents a higher level process than is normally intended by the orthoptic use of the term "suppression". When a person's attention is drawn, without changing fixation, to an object that is not on the horopter he does not normally notice that this is diplopic. This suggests that there is greater physiological repression of the retinal image from one eye than that from the other. Physiological diplopia may, therefore, be a misnomer that is used to describe the artificial situation that, with instruction, can replace physiological repression. It is proposed that tests of sighting dominance aim to measure the strength of monocular repression. In the above example, the subject moves his head so as to bring the least repressed near image into alignment with the distance object.

This principle can be demonstrated if the reader, whilst still looking at the text, directs his visual attention towards his nose. He will be aware of an image of the nose that was previously repressed. Whilst still looking at the text, he may be able to identify, with more difficulty, a second image of his nose that was more strongly repressed than the first. This second image is probably located some way off to the right, indicating that the "true" sighting dominant eye is the right eye. If each eye is closed in turn the dominant eye will become apparent. If, whilst the observer still views a point at reading distance on the medial plane, a pencil is used as a near object instead of the nose then an interesting phenomenon can be observed. When the pencil is held near the ear on same side as the non-sighting dominant eye then the nose acts as a septum so that the pencil is only visible monocularly. As the pencil is moved away from the ear towards the nose then, when it moves into the binocular field of view, the eye that originally saw the pencil will be the sighting dominant eye. Only when the pencil moves near to the medial plane will the dominance change over to the other eye. Sighting dominance, therefore, is a subtle phenomenon that should only be measured under normal circumstances in the median plane.

The ocular repression that has been described seems to be closely linked to visual attention. It is, therefore, a sensory form of dominance and it has been assumed in Figure 3.2 that it relates to an eye rather than a hemifield. This assumption could be investigated by comparing the sighting dominant eye for objects in the binocular field but not on the median plane.

3.1.3 Reviews on Dominance and Dyslexia

Shearer (1966) suggested that the results of sighting tests of ocular dominance were not related to reading performance, although the results of tests based on the controlling eye and retinal rivalry may be more relevant to reading skills. He was wary of the therapy of patching the eye opposite the dominant hand to establish ocular dominance.

Vernon (1971) suggested from the literature that weak or mixed lateralisation was a feature of dyslexia. She discussed handedness, and the difficulties of assessing this and believed that the sighting eye was unlikely to be relevant in dyslexia because it was not related to visual field dominance. The author speculated that weak lateralisation and directional confusion were symptoms of the visual type of dyslexia. She thought that these were linked to errors in sequential ordering and may also directly interfere with the child's capacity to write.

Galaburda et al. (1978) described structural asymmetries in the human brain and noted that asymmetries in the auditory regions and in the Sylvian fissures were present in human foeti and in some apes. They pointed out that the asymmetries could relate to right-left differences in function and may, therefore, account for language lateralisation, hand preference, and possibly childhood learning disabilities and some dementing illnesses of middle life. The theories of Geschwind, Galaburda, and colleagues were described in Section 1.5.3.1.

Pirozzolo and Hansch (1982) reviewed the neurobiology of developmental reading disorders; one of their principal conclusions was that developmental dyslexia was not a single homogeneous clinical entity. They described the autopsy results of 2 patients with RD, the first of whom was found to have, amongst other abnormalities, an atrophied corpus callosum. In the second patient the corpus callosum was normal, but there were several microscopic abnormalities of the left hemisphere. Pirozzolo and Hansch (1982) showed that structural asymmetries in the brain were normal and may provide a favourable anatomical substrate for language development. Two studies had found the opposite trend in dyslexia (i.e., a wider right than left parieto-occipital region). The authors briefly reviewed visual half-field, dichotic listening, and dichaptic shape studies. They concluded that in normal right-handed subjects the left hemisphere was specialised for language functions and the right hemisphere was specialised for certain visual-spatial functions; in dyslexia there was a breakdown of this normal differentiation. They summarised electro-physiological research as follows:

> "Many studies have supported increased localised waveform aberrations, mainly amplitude decrements, on topographical sites overlying the angular gyrus and left parietal cortex, consistent with other neuroanatomical evidence for involvement of this region in dyslexia."

Joynt (1985) noted that a function was not exclusively assigned to a hemisphere, so that cerebral preponderance rather than dominance is usual. Moseley (1988) noted that the concept of inadequate cerebral dominance in dyslexia lacked explanatory power unless it was also assumed that brains that lacked dominance were unable to keep track of the direction of scanning, or cannot tell from which hemisphere a particular letter representation had been sent to some kind of linguistic processor. He pointed out that little was known about how different aspects of eye dominance interrelate and that the basic issue of the reliability of tests of eye dominance needed further study. He criticised static tests since reading is a dynamic process that involves motor control and feedback and thought that alternating suppression would not present problems unless associated with poor motor control.. He thought it unlikely that crossed dominance could affect reading since visual fields, not eyes, were topographically represented in each hemisphere. The author concluded that many studies had been confounded by a referral bias and that, while indeterminate or mixed handedness and eyedness may be significant factors, crossed laterality and left eye sighting preference were of no importance in the causation of specific reading difficulties.

Singleton (1988) noted that many tests and techniques for the diagnosis of dyslexia assess laterality. He criticised the inherent assumption that dyslexia was precipitated by incomplete lateralisation since this did not reliably indicate any neurological abnormality of language development. He explained how studies that used dichotic listening and divided visual fields can give grossly misleading results. He conceded, however, that the relatively high incidence of crossed laterality among dyslexic children still required a satisfactory explanation and suggested that neurological research may provide the answer. He suggested that poor short-term memory may be a correlate of dyslexia and noted that the principal difference between the right and left hemispheres of the brain was that the left hemisphere was more accurate in the resolution of temporal input. Dyslexics children, therefore, were generally found to be inferior in left hemisphere processing of sequential stimuli and in serial memory tasks.

The reviews on dominance and dyslexia are generally inconclusive. This partly results from the wide range of different tests of dominance that have been used. Studies that have looked at specific aspects of dominance will now be reviewed.

3.2 SIGHTING AND SENSORY DOMINANCE

3.2.1 Reversal Theories

Orton (1943) summarised his profound theories on a form of RD, which he called strephosymbolia. He pointed out that reading required the elision of 1 from 2 engrams (monocular images) and believed that faulty or incomplete elision caused a confusion of the orientation or progression of written material and hence reading difficulty. He stressed the need for a battery of tests for eyedness. Some strephosymbolic patients were said to read or write backwards as easily as they could forwards and, since a high percentage were ambiocular and many had crossed or mixed dominance, he concluded that they had a tendency to use the right hemisphere for language. This crossed dominance referred to contralateral hand and eye (by sighting) dominance. The author considered that refractive errors, heterophorias, and abnormal eye movements might contribute to RD, but could not account for reversals. He observed that strephosymbolic children often had one right-handed and one left-handed parent. Orton (1943), in common with many subsequent writers, gave some examples of spelling errors to support his theory. This form of "evidence" seems inappropriate, since a random selection of spelling errors can always be classified into finite groups and, without statistical analysis, used to validate virtually any theory. He concluded that strephosymbolia was caused by "confused cerebral dominance", although it was pointed out that all children make reversals when learning to read.

Shepherd (1956) agreed with Orton that excessive reversals represented a specific form of RD. He investigated 809 children, aged 9-11 years, using the following tests: screening audiogram; V/A; convergence (pen torch as target); span of recognition for letters and numbers, which were exposed for 10 ms in a tachistoscope; sighting eye (5 methods of assessment); handedness (5 methods); dominant foot (4 methods); dominant directions of drawing strokes; mental acuity (Otis Quick Scoring); and reading ability (Gray Oral and Sangren-Woody Silent Reading). He found that, in children of normal intelligence, an increased tendency to make reversals in the drawing test was significantly correlated with decreased reading speed and with reading in a reversed direction. The dominant eye was not related to reading speed although the reading directional pattern was partially related to the dominant eye. Mixed dominance and left eye dominance were so consistently parallel that the same conclusions applied to both. The author's simple test for directional dominance during drawing was interesting and worthy of further investigation. Some of his conclusions, particularly concerning the existence of separate phonemic and sight vocabularies, were years ahead of contemporary thinking.

Spitzer et al. (1959) tested Orton's hypothesis by assessing the incidence of mixed dominance in 103 RD and 288 control children. Ocular dominance was assessed by the subject looking through a small hole in a card that he held in both hands and the dominant hand was determined by self report. The incidences of left, right, and mixed eyedness and handedness were practically identical in both groups; the authors literature review highlighted several studies with similar findings. The selection criteria in this study were vague and the groups were not matched for IQ.

Zangwill and Blakemore (1972) described a patient who, although academically successful, had always had great difficulty with reading. He made many reversals, both of letters and words and his eye movements showed a strong tendency to read from right to left. Word recognition in a tachistoscope was said to be normal. The patient was right-handed for writing, tennis and throwing, but was a left-handed batsman, left-footed, and left-eye dominant (presumably sighting). The researchers noted that this problem, which they attributed to "an irrepressible tendency to move his eyes from right to left", may only occur in some dyslexic people, particularly those who show mixed laterality. The eye movements were not quantitatively analysed.

It is concluded that the literature suggests that a few dyslexic people may have specific difficulty in reading and writing in a left to right direction and make excessive reversal errors. This may be associated with mixed laterality, although there is very little evidence to support the "Ortonian" view that these features characterise a major form of dyslexia.

3.2.2 The Sighting Eye

Fendrick (1935), in a study that was described in Section 2.4, found that the relationship between hand and sighting dominance (tested by Parson's Manoptoscope) were not significantly different in a RD or control group, although there was a tendency for the RD group to demonstrate slightly more mixed dominance. The results of the Parson's Manoptoscope Test were similar to those with a simpler, "pencil test", of sighting dominance.

Clark (1935), in a study described in Section 2.4 measured the reading eye movements of 11 adults with a high exophoria and 11 controls with a normal exophoria; the groups were matched for sex and reading performance. He also determined the dominant eye for sighting and, although the exophoric group made more divergent drifts during reading, the non-dominant eye arrived at the fixation point as frequently as the other eye. He did find, however, more convergent movements in the non-dominant eye. Chakrabarti and Barker (1966) found that the reading achievement of 41 left handed college students was similar to that of 311 right handed male university freshmen.

Rengstorff (1967) assessed the sighting eye in 5,500 patients, who also stated their handedness. The patients came from several sub-groups, of different ages, social status, and geographical distribution. He found that 62% were right-handed and right-eyed and 29% were right-handed and left-eyed. Altogether, 66% were unilateral, 92% right-handed, and 66% right-eyed. Eighty members of this sample had their reading assessed: more unilateral than mixed subjects had above-average reading speed ($p = 0.07$) and comprehension ($p = 0.04$). A further 303 members of the sample were asked if they were fast, average, or slow readers: unilateral subjects were more likely to be fast readers ($p = 0.025$). It is interesting that the author found slight inter-group differences, which may suggest that these parameters varied with different populations.

It is concluded that dyslexia is associated with normal ocular dominance as assessed by sighting tests. There is, however, limited evidence suggesting that, in the general population, unilaterality is associated with better reading. Many other researchers included an assessment of the sighting eye as part of a study of other aspects of ocular dominance and these will be described in the appropriate sections.

3.2.3 The Phi Test

Jasper and Raney (1937) described the Phi Test, which was said to assess the sensory ocular dominance. In this test the subject fixated a distant or near light, which were alternated at a frequency of 1.5 cycles/second.. When, for example, the distant light was illuminated the subject had been fixating at near and hence the distant target was seen in diplopia. The right eye's diplopic image would appear to have moved to the right and will be imaged in the left hemisphere; and vice-versa for the left eye's image. When the near target was illuminated the opposite conclusions pertained; i.e., the right eye perceived a movement to the left and the image was represented in the right hemisphere. Hence, if movement was reported to the right at near fixation and to the left at far fixation right ocular dominance was indicated, and vice-versa. Reports of a simultaneous movement in both directions or of an alternation of movement indicated either unstable dominance or ambilaterality. The authors assessed this test with 44 patients. The reliability, when subjects were tested on 2 occasions separated by 4 weeks, was found to be 90%; although there was a possibility that subjects remembered their initial response. When the Phi Test was compared with other tests of dominance the reliability was found to compare well, and it seemed to be assessing a different parameter from monocular sighting. The authors did not consider the effect of a heterophoria on the result, and there also seemed to be two practical problems with this test. Firstly some subjects needed 15-25 mins. before they perceived the phi-movement; this raises the question of whether, after this period of time, they answered objectively or just to please (or silence) the examiner. Secondly, the test seemed to be very subjective, both for patient and examiner.

McFie (1952) examined 12 patients who seemed to have been a heterogeneous group of severely learning disabled individuals. Some of them were virtually illiterate, some had abnormal EEG's, and one had been certified under the Mental Deficiency Act. The author assessed the Phi Test, hand preference (best simultaneous writing), sighting eye, IQ, and reading ability. He found a close agreement between the dominant hemisphere with the Phi Test and that indicated by handedness, although most of his patients reported little or no apparent movement with the Phi Test. He disagreed with Orton's contention that the basis of dyslexia was a confusion in cerebral dominance and concluded, instead, that the neurophysiological organisation corresponding to dominance had not been normally established in either hemisphere.

The Phi Test theoretically provides a sensitive measure of hemifield sensory ocular dominance and it would be interesting to compare cortical sensory ocular dominance with other measures of laterality in dyslexic and control samples. This test, however, appears to have severe practical limitations that may prevent such a study from reaching useful conclusions.

3.2.4 Retinal Rivalry

Moseley (1988) investigated several aspects of dominance, including retinal rivalry. This study is described in Section 3.2.7.

Logothetis and Schall (1990) measured behavioural eye dominance by retinal rivalry in the Macaque monkey. This was found to vary significantly over time, between individuals, and as a function of interocular contrast difference. Their results suggested that a motion signal was derived from the suppressed eye despite the phenomenal dominance of the other eye. They concluded that suppression during rivalry may not actually represent blindness of the suppressed eye, instead it appeared to be an active inhibitory process at a relatively advanced stage of the visual system that prevented the suppressed stimulus from reaching conscious awareness.

The limited data on this unnatural test of sensory dominance preclude firm conclusions. Gilchrist (1976) noted that the results of tests based on retinal rivalry may be confounded by differences in the monocular stimuli. Since these tests require dissimilar stimuli to prevent fusion, his observation reveals an inherent weakness of this paradigm. This could be overcome by reversing the monocular targets over several trials and this method is advocated for future research.

3.2.5 The "Controlling Eye" on The Keystone Instrument

The Keystone Ophthalmic Telebinocular is a stereoscopic device that has been used as a screening instrument. Up to 29 target cards have been used to assess many aspects of visual function including several tests of the dominant eye (Henson, 1983, pp. 232-237). The term "controlling eye" has often been used to describe the dominant eye as measured by this apparatus. This was probably to differentiate these test results from sighting dominance.

Berner and Berner (1953) assessed the controlling eye using the Keystone instrument with the visual skills test (retinal rivalry) and binocular skills test (segmented reading). They analysed the results from 500 patients and concluded that crossed or unstable dominance was significantly correlated with RD. They treated such cases by changing the preferred hand, prescribing glasses, or occlusion. This study was also weakened by: inadequate selection criteria, a sparsity of results, and the absence of referral details and statistical analysis.

Shearer (1966) briefly described the results of screening tests on 220 children. These were selected by their teachers as being at least one year behind in reading. The screening tests, on the Keystone instrument, revealed that 46% of the RD group had "mixed preference (eye, hand, and foot)". The absence of a control group, data, or test details makes these results difficult to interpret.

Helveston et al. (1970) compared 310 children, who were the total population of a school between the ages of 8 and 11 years, with 67 children from a dyslexia clinic (diagnostic criteria were not given). They analysed the following variables: reading ability (from school records); IQ (school records of a group administered verbal test); V/A; handedness; footedness; and sighting eye. The controlling eye was assessed in 2 ways: with the Keystone stereovision cards - if the occlusion of one eye caused an increase in

V/A in the opposite eye, the occluded eye was considered the controlling or dominant eye; and by the control of retinal rivalry with the parrot and cage targets in the Keystone, if the 2 alternated more often than every 4 seconds there was poor control. The authors found no correlation between any of their measures of laterality and reading ability.

Bettman et al. (1967) examined 47 dyslexic children who were diagnosed by strict criteria, and 58 controls, who were good readers. These groups were not matched for IQ. Some of their findings are given in Section 2.4. Laterality was assessed with the following tests: hair whorl, sighting eye, controlling eye on the Keystone instrument, arm extension, crossed arms, handedness, and lateral awareness. The groups were not significantly different in any of these measures of dominance, or in the incidence of various combinations of mixed dominance. The authors criticised many therapies that attempted to correct crossed or unstable dominance in the RD.

Simons and Grisham (1987) criticised screening tests, particularly those based on the Keystone instrument, on grounds of reliability and validity. They also noted that these tests created an artificial environment and lacked a theoretical foundation.

The widespread use of the Keystone instrument for screening has facilitated the assessment of several aspects of ocular dominance. Many of these studies have suffered from methodological weaknesses and the few thorough studies have failed to find any significant correlations between reading ability and crossed or abnormal laterality.

3.2.6 Cerebral Dominance and Hemispheric Specialisation

This area has been fully reviewed by Beaumont and Rugg (1978). Only selected studies will be included in the present review.

Zurif and Carson (1970) investigated 14 poor readers of unspecified age, most of whom appeared to be at least 2 years retarded in reading; and 14 control subjects. The groups were matched for intelligence, which was in all cases within normal limits, and the subjects were said to be free from "visual deficits" (no details were given). The researchers assessed the following variables: hand preference; relative manual dexterity; auditory temporal processing; visual temporal processing; auditory-visual integration; and dichotic listening (DL). A typical procedure for this last experiment was described by Chasty (1979) and involved presenting 4 pairs of digits (one set of 4 to each ear), over a period of 2 seconds. The subject then noted the digits that he remembered and the procedure was repeated 25 times; the channels were reversed after 13 trials. The percentage of correct recollections for each ear was recorded as a measure of dominance.

The hand preference of the 2 groups did not differ significantly. In all of the other tests there was a significant difference between the groups, in particular there were noticeable asymmetry effects on those tasks generating left- and right-side scores. The control group was more right-ear dominant and the dyslexic group had generally less manual dexterity. The results were said to suggest incomplete hemispheric specialisation, which was thought to result from a maturational lag in developing the laterality of mechanisms subserving language. The dyslexic group demonstrated a deficit with the temporal aspects of patterned non-verbal auditory stimuli and impaired intersensory integration, which was thought to result from deficient temporal processing.

Naidoo (1972, pp. 98-109) presented evidence suggesting that a subgroup of dyslexic individuals with some form of cerebral insult demonstrated multiple minor neurological signs. These included eye movement abnormalities, visuo-spatial and visual retention deficits, and indeterminate hand or foot preference.

Sklar et al. (1972) used EEGs to investigate 12 dyslexic and 13 control individuals; the groups were not matched for intelligence. They found that during reading tests the coherence in the right hemisphere proved to be a better discriminator than that in the left.

A review by Dimond (1973) explained the limitations of assessing ocular dominance by sighting and how this has led to hemi-field studies. These had found that letter recognition was better if these were presented in the right field and dot recognition was normally better when presented in the left field. Visuo-spatial ability (for a dot) was better differentiated in males than females. In right-handed people, the responses of the right hand were more sensitive to interference from the addition of a contralateral response than were those of the left ; the opposite applied to left-handed individuals. The author's own studies had found a more rapid organisation of motor signals for language aspects of visual perception in the left hemisphere although, for non-language tasks, this was more rapid in the right. He stressed that the non-dominant hemisphere for a given function was not necessarily unable to carry out that function.

McKeever and VanDeventer (1975) believed that "true" dyslexia was caused by a subtle neurological defect and would persist, therefore, into adulthood. They noted that the literature had failed to establish a relationship between mixed hand-eye dominance and cerebral language dominance. They felt that DL studies had been inconsistent, whilst studies of tachistoscopic lateral word recognition performance had found that poor readers showed no impairment at the level of isolated word recognition ability and demonstrated superior recognition in the right visual half-field. The author's research compared 9 carefully selected dyslexic adolescents with an equal number of age-matched controls and used co-variant analyses to control for the effect of intelligence. Their first experiment involved unilateral and bilateral tachistoscopic word recognition and a tachistoscopic recognition report-time task for single lateralised letter stimuli. Their second experiment, which was conducted a year later, re-administered these tasks with modifications and added dichotic digits and motor reaction time-stimulus detection tasks. They concluded from their results that right handed, chronic dyslexic people demonstrated left hemisphere language specialisation; normal interhemispheric processing delays for single letter stimuli; impaired visual and auditory processing of simple language stimuli (unlike non-dyslexic poor readers); auditory memory deficits for verbal material; and, possibly, an additional deficit of left hemisphere visual association area function.

Yeni-Komshian et al. (1975) used DL and visual hemifield techniques to investigate 19 good and 19 poor readers. The subjects were all right-handed, but were not matched for age, sex, or intelligence. No individual selection criteria were given, although the mean reading grade of the poor readers was 3 years behind that of the controls. For the DL test 30 series of 3 pairs of numbers were presented at the rate of 1 per second. The subjects were instructed to recall the digits heard in a specified ear (the attended ear) before recalling those heard in the unattended ear. Two paradigms were used for the visual half-field presentations; it is not clear, but seems likely that these were carried out binocularly. In the visual-half field presentation of numerals (VHF-N) five different digits were presented in numeral form. These were situated either centrally (to control fixation) or 4 degrees offset to the left or right. The exposure time was 189 ms and 2 sets of 32 trials were administered. In the second paradigm, the visual half-field presentation of words (VHF-W), the numerals were presented in upper case word form (e.g., TWO), which were arranged vertically to prevent scanning. The poor readers showed worse performance than the good readers on the VHF-W tests and at reporting the attended ear in the DL. The finding that the poor readers had larger discrepancies between left-right scores than the controls did not support the hypothesis that poor readers were not as well lateralised as normal readers. This trend was only statistically significant for the 2 visual tests; it was thought that this may reflect the visual nature of the poor readers' deficit. The large discrepancies between left-right scores resulted from the left VHF scores. The authors concluded that poor readers either suffered from some kind of processing deficit in the right hemisphere or that the transmission from the right to left hemisphere was degraded. This study did not control for eye movements during the VHF experiments and it seems that the individual relationships between hemispheric dominance on the DL and VHF tests was not analysed.

Witelson (1977) hypothesised that in normal readers the right hemisphere was specialised for spatial functions and the left hemisphere for linguistic (sequential) functions. She suggested that in dyslexia both hemispheres carried out spatial functions and the left hemisphere still carried out, although deficiently, linguistic processing. She believed, therefore, that dyslexic individuals had a deficiency in the linguistic, sequential, analytic, cognitive mode of information processing and an intact or even overdeveloped use of the spatial, parallel, holistic mode. Her subjects were an unspecified control group and 85 right-handed dyslexic boys, aged 6-14 years; precise diagnostic criteria were not given. Two tests were used to investigate hemispheric specialisation for spatial processing. The first was "dichhaptic stimulation": different meaningless shapes were presented simultaneously to each hand for identification by touch alone In the second test pairs of identical or different figures of people were tachistoscopically presented in either the right or left visual half-field; the pairs had to be identified as same or different. To investigate hemispheric specialisation for linguistic processing a simple DL paradigm was used. A fourth experiment dichhaptically presented letters that had to be named by the subject; this required both spatial and linguistic processing. The first experiment showed a significant tendency for the control group to use the right hemisphere for spatial processing whilst the dyslexic group showed a significant tendency to use both hemispheres. The second experiment concurred with the first, although the 2 groups did not differ in total accuracy for either test. In the third experiment both groups were found to use the left hemisphere for language processing, although the dyslexic group's total accuracy was lower. In the final experiment, the control group showed a non-significant specialisation for the left hemisphere whilst the dyslexic group showed a significant tendency to use the right hemisphere rather than the left. The author concluded that the results supported her hypothesis. Her theory specified, in contrast to a maturational lag, a qualitative neural deficit which was manifested not just as poor reading but as a "specific cognitive deficit". She further hypothesised that normal girls have bilateral representation of spatial functions and a non-deficient left hemisphere (unlike dyslexic boys). This paper did not give full details of the methods and did not investigate the homogeneity of the results.

Beaumont and Rugg (1978) thoroughly reviewed neuropsychological evidence and theories relating to lateralisation of function in dyslexia. They felt that it was impossible to draw any firm conclusions from the results of EEG studies. The results of studies of DL were also equivocal, but did not suggest abnormal function in dyslexia. The results of visual hemifield experiments were slightly confusing but probably suggested that there was an unusually small left hemifield advantage for verbal tasks in dyslexia. The authors criticised theories that dyslexia was caused by a lag of maturation of laterality; they felt that this would cause a wide range of difficulties in addition to dyslexia. They also noted that left- and mixed-handed people have an increased dissociation between auditory and visual language laterality and reviewed the theory that dyslexia resulted from a deficiency in visual-verbal (and hence inter-hemispheric) integration. These reviewers then gave their own hypothesis that dyslexia is caused by a functional dissociation between the lateralised cerebral systems for auditory and visual language processes. They pointed out that this could result from Geschwind's disconnection syndrome. It is not clear whether this was considered to be the "cause" of all cases of dyslexia.

A study by Mykel and Daves (1979) proved the existence of a dominant or controlling ear in right-handed subjects. It would be interesting to repeat this experiment with left-handed individuals.

Chasty (1979) investigated the hypothesis that at birth and in early childhood the hemispheres have an "equipotentiality" for language and that, as the child matures, language processing becomes lateralised in the left hemisphere. This lateralisation was thought to proceed rapidly between the ages of 2 and 5 years and then more slowly until adulthood. The author divided 99 normal children into 6 age-groups between 5 and 11 years. Each group had a mean IQ of 100, a normal distribution of reading ability, and equal sex ratios. He assessed hemispheric dominance using a DL paradigm and repeated the testing one year later. There was a significant right ear superiority in every age group, indicating that left hemisphere specialism for language was already established by the age of 5 years and did not develop significantly thereafter. He then used this technique to investigate 27 dyslexic children (26 males), of average age 11.9 years, mean reading age 9.5 years, and with a mean IQ of 111. These were diagnosed by an educational psychologist on the basis of several tests, and children with a history of hearing disability or who were on "the left side of the laterality dimension" (criteria for this were not given) were not included. A control group of 94 children were taken from his first experiment; the age and IQ of the groups were not closely matched. The control group had a strong right ear advantage, and the dyslexic group had an equally strong left ear advantage. These findings were statistically significant and suggested a right hemispheric control of language in dyslexia. The author noted that a few members of the control group also had right hemisphere control of language. He hypothesised that this right hemisphere language specialism required complex information transmission within the brain across the corpus callosum. He thought that in dyslexia this was disrupted by a neural "interference" mechanism, which prevented the development of an efficient high level of control over the separate visual, auditory, and kinaesthetic skills that are the basis of a child's language performance.

Pirozollo and Rayner (1980) noted that the reaction time for eye movements to the right was normally shorter than for those to the left, and that this could be explained as a learned response from reading or as a structural corollary of left hemisphere, which is involved in rightward saccades, specialisation for visuomotor control. They investigated this in 16 adults who were normal readers and half of whom were left handed. Words or asterisks were presented on a CRT at various horizontal eccentricities, and the subject's eye movements were recorded. The right handed subjects all demonstrated decreased reaction times to parafoveal stimuli presented in the right visual field, whereas the left handed subjects, as a group, showed no such asymmetry. Some members of the left handed group showed no asymmetry, whilst others were faster in one or the other direction. The authors also found a linearly decreasing reaction time to stimuli within 10° from fixation and a linearly increasing reaction time to more eccentric targets; this bi-modal distribution suggested that there were different neural programming mechanisms for saccades within and beyond 10-15° from fixation. The authors thought that the shorter saccades were cortical in origin, whereas the longer ones were mediated through the superior colliculus. It was concluded that right handed people were "gaze lateral" whilst left handed people were not. This was thought to suggest that in right handed people the left hemisphere was superior at processing visuomotor information.

Hughes (1982) reviewed Electroencephalogram (EEG) findings in reading disorders. He described the use of alpha asymmetry for determining the dominant hemisphere, which was believed to be a more consistent method than using differences in the VEP. Studies had found that dominance of hemispheric processing was a function of task processing demands. Hughes concluded that RDs were best explained by a multiplicity of defects or lesions.

Van den Honert (1987) briefly suggested that there may be a defective corpus callosum in dyslexia. She felt that this would affect functions that require quick and efficient transfer of information across the commissures and could explain such findings in dyslexia as: poor convergence, unstable ocular dominance, poor tracking, and poor "matched focusing in near vision" (this condition was not explained).

It is clear from this limited review that the evidence from experimental neurophysiology on the role of cerebral dominance and hemispheric specialisation in dyslexia is highly equivocal. Some authors have implicated right, and some left, hemisphere deficits in dyslexia, whilst others have suggested that the integration of information across the hemispheres is abnormal. Recent theories on hemispheric specialisation in dyslexia (*see* Section 3.3) have failed to clarify the situation. The idiosyncratic cyto-architectonic cortical abnormalities that were described in Section 1.5.3.1 may account for some of the diverse findings in the literature and explain the heterogeneous nature of the correlates of dyslexia.

3.2.7 Miscellaneous Studies

Spache (1943) designed test cards for a stereoscope so that a child read a story, some words of which were seen by both eyes and some by each eye. The words that were seen monocularly were redundant to the meaning of the passage and would have been perceived as gaps if one eye was being suppressed. The proportion of words read with each eye was thought to reveal the relative use of the monocular images during normal reading. This hypothesis is questionable because of the artificial nature of the test. The author found that some children used the eye with poorer V/A as their "leading eye" and he believed that this was a cause of RD.

Benton et al. (1965) studied 250 "dyslexics" (no selection criteria were given) using a test battery that included tests of: sighting dominance, which eye was easier to wink with, which eye was better at counting dots, and retinal rivalry. They found that 93 of the children had crossed dominance, 53 had mixed dominance, and 104 had incomplete dominance; unfortunately, it is unclear which test results or what criteria were used for these diagnoses. The results were related to the finding of convergence insufficiency in their sample (*see* Section 2.4) and the subjects were said to respond well to treatment. This paper was weakened by the lack of: a control group, subject selection criteria, and quantitative analysis of reading performance before or after treatment.

Benton et al. (1969) noted that other workers had failed to replicate their findings of atypical eye dominance in dyslexia. They re-analysed their results and described some different conclusions. They still found an increased incidence of crossed or mixed dominance in dyslexia but some good readers also showed similar patterns. This applied to the sighting or controlling eye, or to the results of any other test of ocular dominance. They noted that dyslexia was associated with a greater incidence of mixed hand laterality and confusion about right and left orientation; this was explained as evidence of neurological dysfunction or a maturational lag. The authors also concluded that tests of retinal rivalry were of no value in the routine evaluation of dyslexia. They reviewed over 1,000 dyslexic children who they had treated to change or establish eye dominance. The reading performance had improved in about two thirds of these, but they acknowledged that the treatment had included medication and extra teaching, as well as an inevitable placebo effect. The authors had retested those children who had improved and had found no consistent parallel between the improvement and the reversal of previously "abnormal dominance". They did, however, find that about 15% of those under treatment performed distinctly better when one eye was occluded or dilated. The authors could not distinguish this group from the others; they may represent a heightened placebo effect. They concluded that eye dominance was *not* an important variable in dyslexia, although it was suggested that occlusion treatment could be attempted if other therapies were not working.

Brod and Hamilton (1973), in a study that is described in Section 2.4, used induced aneisokonia to investigate the effect of a disturbance of binocular vision on reading. Their subjects were 162 children, aged 10 years, comprising equal numbers of good, poor, and average readers. The subjects read 3 passages, of equivalent difficulty, with the intervention of a 1.25 x 90 aniseikonic lens in front of the right eye, the left eye, and without the intervention. The results showed an interesting trend, which was not commented upon by the authors. When the aniseikonic lens was placed in front of the right eye the good readers read much better, and the average readers slightly better, than when it was placed in front of the left eye. However, the poor readers read much better when the lens was placed in front of their left eye than when before their right eye. The present author has re-analysed the data to show that these differences were statistically significant (chi-squared test; $p < 0.001$). The results of this study suggest, therefore, that right eye dominance prevailed in the good readers and left or mixed eye dominance was more common in poor readers.

Moseley (1988) used a battery of dominance tests to investigate several groups of children. The first sample of 57 children had a specific spelling disability, whilst the second group of 69 children were "average spellers". The third group had low, and the fourth group high, spatial ability; this classification was made using the author's own test of spatial visualisation. It was claimed that good performance at this test suggested "right-brainedness" (spatial ability superior to verbal ability), whilst poor performance suggested left-brainedness; the author noted that this classification lacked objective evidence. The children in these 4 groups came from the same school and were aged between 8 and 10 years. A fifth group of dyslexic subjects (defined as reading age 18 months or more below chronological age) had a wide age-range of 7 to 16 years. No measures of intelligence were available and the groups were not matched for age or sex. Other weaknesses of this study were that each group performed only some of the tests in the battery and a blind protocol was not used.

Handedness was assessed in 2 ways: the hand used to write, and the ease with which fingers could be lifted when the hands were placed palm down on a table. Visual field dominance was assessed with 3 tests: the Phi Test (*see* Section 3.2.3); the duration of figural after-effect (full details of this test were not given); and from the subjects' drawings - it was assumed that right visual field dominance would be manifested by the "head" of the object being towards the left hand side of the drawing space. Sighting eye dominance was assessed with the Asher Test; if handedness was a major confounding variable this test would suggest ambidexterity. Sensory ocular dominance was assessed by retinal rivalry, where different colours were seen by each eye; Michaels (1972) noted that the hue and saturation of the colours confounded the results of such a test. The "binocular reading test" also assessed the sensory ocular dominance; the subject read a series of 3 letter words in a stereoscope in which one letter was different for each eye. For example, "web" might be exposed to the right eye and "wet" to the left; the number of words read by each eye was a measure of the dominance, and this test was said to have a test-retest reliability of 0.77. For 2 final tests of ocular dominance the monocular speeds at matched search tasks and then matched passages were compared. The subjects commenced both tasks with the :"non-preferred eye"; it was unclear how this was determined.

Moseley (1988) found that the results of the 2 tests of handedness were significantly concordant, whilst those of the tests of visual field dominance were not significantly related to one other. The results of the eye dominance tests were not significantly related, except for the search task and the reading speeds; this may have been a practice effect since both tests were carried out first with the same eye. The results of the tests of "brainedness" were not significantly related to the results of the other dominance tests. The results for the groups with specific spelling disability, dyslexia, and with normal spelling skills were compared. The dyslexic group showed a statistically significant increased tendency to suppress the right eye during retinal rivalry than the other groups. Interestingly, 3 members of the dyslexic group were untestable since they could not achieve fusion. The results of the other tests of dominance were similar in the different groups. Within the "high spatial ability" group, the subjects who showed a strong tendency to suppress the left eye were significantly advanced in both reading and spelling compared with those who tended to suppress the right eye or who did not show a strong tendency to suppress. A similar analysis did not reveal any significant results for the "low spatial ability" group or for those with specific spelling problems. Within the dyslexic sample, the small group of 5 boys who showed total suppression of the right eye had significantly lower reading ages and were significantly slower at the reading and search tasks.

Moseley (1988) concluded that different kinds of eye dominance tests measure unrelated functions and that mixed or left handedness was not associated with spelling problems. Eye dominance, as measured by conventional sighting tests, was said to be irrelevant to the assessment and treatment of reading and spelling problems. A general right field bias had not been associated with higher levels of competence in processing script, although he pointed out that none of his stimuli were letters. It was noted that all 5 dyslexic boys who showed total right eye suppression during retinal rivalry rotated the paper when performing the scanning test, and 3 of these also used right-to-left scanning on some lines. He hypothesised that this suppression may result from poor binocular co-ordination, although he could not explain why only right eye suppression was found to be a problem. It would have been interesting to relate this to a test of motor ocular dominance. His comment that both muscle imbalance and suppression may need to be present to cause problems did not reflect the conventional explanation of suppression as a compensatory mechanism for binocular anomalies (Giles, 1949, p. 156; Mallett, 1988; Stidwill, 1990, p. 72).

3.3 Motor Dominance: The Dunlop Test (DT) and The Reference Eye

Mayou (1962) used sighting tests to assess ocular dominance and described 3 types of "incorrect dominance". These were when the non-dominant eye had the better vision, crossed dominance, and a combination of these two. She reported the anecdotal observation that crossed dominance or "over-dominance", which was when one eye was too strongly dominant, could cause RDs. She felt that this was associated with esophoria at distance and poor convergence at near, and claimed successful treatment by giving reading exercises with the dominant eye covered in order to encourage the use of the non-dominant eye. This appears to be in direct contradiction with later therapies, which are described below.

Stone et al. (1973) severed one optic tract of 4 monkeys, killed them after 6 to 12 months, and then carried out a microscopic analysis of the ganglion cells. They found that there was a central strip, approximately 1° wide, where the visual fields overlapped. They explained that these results were unlikely to be related to macular sparing, which occurs in hemianopia. Victor et al. (1991) have recently used visual evoked potentials to show that the bilateral cortical representation of the nasal half of foveal retina found in primates is likely to be present also in man. They concluded that, to ensure the continuity of the visual field at the midline, the connections between visual cortices must travel between the posterior aspect of the corpus callosum and that there must be bilateral projection of the midline retina.

Dunlop et al. (1973) suggested that the eye that controlled binocular functions could be different to the sighting eye or the dominant eye from tests of suppression or retinal rivalry since these all related to monocular visual tasks. The authors described the Dunlop Test (DT), which was carried out on a standard synoptophore using slides F69 and F70. These depicted a small house with 2 trees, a large one seen by one eye, and a small one by the other. These indicators were within 1.5° to 2° of fixation, and the subject fixated the central door during testing. The examiner slowly and steadily diverged or converged the tubes from the angle of fusion. Before fusion was lost, the subject normally reported that one marker moved and the eye which saw this marker was said to be the non-dominant eye. This test, therefore, used forced divergence to induce a fixation disparity; the eye that maintained precise fixation could be described as dominant for this motor task.

Dunlop et al. (1973) investigated the incidence of visual defects and crossed laterality in 15 reading retardates and 15 advanced readers. The dyslexic children were not selected by empirical criteria and the groups were not matched for age or intelligence. The ocular examination, which was mainly carried out according to a blind protocol, included the following tests: cover test and motility; convergence; single letter V/A; dissociated heterophoria at distance and near; assessment of simultaneous foveal perception; fusion; fusional amplitude; stereopsis on a synoptophore (various models were used); preferred writing hand; "controlling eye" with the DT (convergence and divergence, 1 trial); the non-suppressing eye on a stereoscopic test; and the eye to move least under cover. The cover test result was only recorded as an esophoria or exophoria ; the magnitude of the deviation and viewing distance were not given. The NPC was recorded on an arbitrary 5 point scale; the use of a continuous variable would have afforded greater sensitivity.

Dunlop et al. (1973) found that the dyslexic group had significantly poorer convergence and stereopsis and a significantly greater incidence of crossed handedness-controlling eye. Various combinations of these variables were used to obtain greater specificity in differentiating the groups. The various visual measures were summed across subjects to give a "total visual score". There was a low, but significant, correlation between this score and the reading accuracy and rate and IQ. The relationship with reading accuracy was still significant when the age and IQ were individually partialled out. In their conclusion the authors noted that all the children had been declared normal in routine visual examinations and suggested that it was feasible to change the dominant eye to improve laterality problems.

Dunlop and Dunlop (1974) described a theory based on Stone et al.'s (1973) finding that a central overlapping strip of retina from each eye was represented in both hemispheres. They hypothesised that mirror reversals would occur unless the visual input to the speech and motor dominant hemisphere was organised so that callosal transfer was either consistently avoided or accepted. They proposed that this central region was structurally and functionally different to the lateral areas. The central strip was thought to lack an innately dominant eye so that the projected field of one eye was used as a reference against which the stimulus from the other eye was compared. The size of this central area was not given, although the researchers later suggest that it was 1.5° to 2° wide (Dunlop, 1976). This theory may be complicated by more recent research (Hubel, 1988) showing that the foveal representation of the cortex is divided into right and left eye strips. Dunlop and Dunlop (1974) thought that the narrow central overlap was matched by a much wider binocular overlap, which was mediated by the corpus callosum and was the site of fine stereopsis. They believed that the image of one eye was maintained in central memory as a separate, reversed, image from that of the opposite eye. The lack of a stable reference eye (as measured by the DT), therefore, resulted in the mirror reversals of dyslexia. They believed that the most common basic error in dyslexia was reversals and also stated that a sensitive stereopsis test should be able to detect the effects of an unstable reference eye.

Dunlop and Banks (1974) examined 15 subjects, 14 male and 1 female, who were selected from the case studies of a remedial teacher, and an equivalent number of age- and sex-matched controls. They carried out several orthoptic tests, according to a blind protocol, that included V/A, convergence, stereopsis, and the DT. They found that the triple combination of esophoria at distance, defective stereopsis, and crossed dominance with the DT was highly correlated with RD; 60% of the dyslexic group had this combination. This paper suffered from several methodological weaknesses: poor selection criteria; imprecise IQ matching; a failure to take account of refractive errors; the use, with some patients, of synoptophore slides (F9 and F10) that were too large to be described as "macular"; and a lack of details on the tests of heterophoria. The esophoria that the authors referred to was the Group IV type (Mayou, 1962); this was a small esophoria at distance combined with small exophoria at near. In cases of RD it might be more appropriate to describe this as exophoria at near. Dunlop and Banks (1974) found that 67% of their experimental group exhibited poor convergence. It is unclear how many of these subjects were in the "triple combination" group; if there was considerable overlap then the results could be explained as poor convergence causing exophoria at near and impaired stereopsis. This does not, however, explain the correlation with crossed dominance on the DT .

Dunlop (1975) briefly described some results obtained with 345 children who appeared to be learning disabled (no diagnostic criteria were given). Crossed or unstable dominance (handedness and reference eye) was demonstrated by 250 of these, although without a control group the significance of this was unclear. Some results of occlusion therapy were also reported;these seemed to be based on the patient's subjective reports. Three of her patients made a change of hand for writing with "favourable results" and 2 boys who had suffered broken arms during the pre-school period had crossed correspondence and did not respond to occlusion therapy. She also found that 34 of the patients had convergence insufficiency and normal dominance and 10 manifested intermittent strabismus. Two cases of Brown's superior oblique tendon sheath syndrome were in this group and there were no cases of constant strabismus. She stressed that when unstable dominance was treated by occlusion it was important to give convergence exercises.

Dunlop (1976) noted that their referent eye test was based on Dunlop and Dunlop's (1974) theory and Ogle's (1962) observation that "the phenomena of directional difference of fused disparate images within Panum's area are a possible basis of tests for ocular dominance." Dunlop (1976) advocated divergence of the synoptophore tubes during the DT because convergence caused the patient difficulty in observing the slides due to the effect of accommodation. This may represent a weakness of the test, since in normal binocular vision the vergence of the eyes does not change significantly without a corresponding change in accommodation. The motor dominant eye during the extremely unnatural conditions of divergence, independent of accommodation, from the primary position may be quite different from the motor dominant eye during normal binocular vision. The author described 5 possible responses to the test: right or left reference, alternating reference, undeveloped reference, and no reference eye because of suppression of 1 eye in the central binocular field. The test was said to be suitable for most children over the age of 4.5 years.

Dunlop (1976) described a study of 15 dyslexic (varied selection criteria) and 15 control children, who were aged 7-12 years and had a similar mean age and IQ. Inconsistent selection criteria were used for the dyslexic sample and and a blind protocol was not adopted. The results of this study are summarised in Table 3.2. She concluded that the "triple combination" was an effective diagnostic factor for "the visual type of specific dyslexia."

condition	p <
convergence deficiency	0.005
defective stereopsis	0.025
crossed handedness-reference eye	0.001
combination of esophoria, defective stereopsis, and crossed correspondence	0.001
crossed handedness-sighting eye	NS

Table 3.2 Results obtained by Dunlop (1976). "NS" is not significant and the esophoria refers to a small esophoria at distanced and a small exophoria at near.

Spooner (1978) carried out a small pilot study of 53 children, aged 8-9 years, 45 of whom attended remedial reading classes and 8 of whom acted as controls. The subjects were investigated with several orthoptic tests and the DT, which was repeated 3 times. None of the subjects demonstrated Dunlop and Banks' (1974) triple combination. Of the 19 children who had unstable dominance (by the DT) she found 5 who had weak convergence, 2 who had defective stereopsis, but none who had both. Although all the children had passed the school eye test, 4 eyes were found to have vision of 6/12 or worse. The reference eye was on the opposite side to the preferred hand in 17 of the RD subjects and 2 of the controls. Crossed laterality was treated with occlusion in 8 of the RD subjects, 1 of whom improved. She said that convergence exercises were unsuccessful, although the exercises were not described. None of the findings were statistically significant, partly due to the small size of the groups. It was not stated whether the DT results were obtained with slides F9/F10 (monocular markers 3° apart), or F69/70 (monocular markers 1.5° apart).

Dunlop (1979) briefly described her recent research, with 150 randomly selected pre-school children, showing that lateralisation of the central visual field was often still immature at the age of 6 years. Only 1% of all learning disabled individuals were said to have her "specific dyslexia of the visual type". Treatment, by occlusion of the opposite eye to the preferred hand for all near vision, was normally required for 1 to 1.5 years and was unsuccessful in some children who seemed unable to change their reference eye.

Bishop et al. (1979) examined 147 unselected children, aged 8.5 years. They tested several variables, including the following: intelligence (WISC-R), reading ability (Neale), cover test, convergence, and stereopsis. The DT was performed as many times as was necessary to establish the nature of the response (at least 3 times). The cover test and stereopsis results did not correlate with either intelligence or reading age. There was a low correlation between poor reading scores and mild convergence insufficiency, although there were insufficient numbers for meaningful statistical analysis. Reading ability was not correlated with sighting dominance, but was significantly inversely correlated with an unstable reference eye. Further statistical analysis showed that this relationship resulted from a correlation between low IQ and an unstable response on the DT. To confirm this finding, 17 of the children who were poor readers (15 months retarded) were matched for age and IQ with controls of normal reading ability. The incidence of orthoptic conditions, including unstable dominance and Dunlop's triple combination, was similar in the 2 groups. This study suffered from a few methodological weaknesses: no refractive data were available, unrealistically easy pass criteria were adopted for the NPC and stereopsis tests, and if a child reported no movement of either monocular marker on the DT this was recorded as "no reference". The authors concluded that the DT was difficult to administer and that this caused the result to be dramatically influenced by the child's intelligence. They also mentioned that the DT results obtained with abduction and adduction seemed to differ considerably. During the normal DT the eyes abduct from the primary position (for distance vision), without changing accommodation. This is unnatural and is quite unlike oculomotor behaviour during reading, when the eyes are normally adducted.

Bedwell et al. (1980) used a video camera to record the eye and head movements during reading of 40 children. The subjects were aged between 13 and 14 years, and 25 of them were 2 or more years retarded in reading. The recordings were assessed, without sound, by independent observers who were unaware of the children's reading ability. They defined the controlling eye as the eye that appeared most likely to maintain accurate fixation and one of the variables that they assessed was indecision as to the controlling eye. They suggested that this was a sign of unstable binocular co-ordination and may result in perceptual anomalies. The dyslexic group were significantly worse than the controls in the following variables: indecision over controlling eye; general ocular instability; unequal eye movements; tendency to diverge whilst reading; and compensatory head movements.

Stein and Fowler (1981) believed that the absence of a *stable* reference eye caused "visual dyslexia". They modified the DT by repeating it 10 times and diagnosed unstable dominance if the same eye was dominant less than 8 times out of 10. They gave the following theoretical account of the neurophysiology of the DT:

> "In the test each eye is made to move in an opposite direction; so in the first instance oculomotor signals about its movement probably originate in the hemisphere contralateral to that eye, whilst retinal signals about the tree it views are projected to the ipsilateral hemisphere. Yet only the information deriving from one eye is successfully associated with retinal signals about the tree it views, presumably because of the interhemispheric connections. This gives rise to the illusion that one of the trees moves. Such associations are not made for the signals coming from the other eye. Hence the DT is able to identify the eye whose oculomotor and retinal signals are successfully integrated (i.e. the eye contralateral to the tree that appears to move) as the dominant one".

Stein and Fowler (1982) described a "double-blind" study of 80 dyslexic and 80 control children, who were matched for age and performance IQ. The reading age of the dyslexic subjects was more than 18 months behind their chronological age (mean 10 years), and their performance IQ's were normal. The modified DT was used with slides F9 and F10. Unstable dominance was manifested by 63% of the dyslexic compared with 1% of the control group. Eye examinations revealed no differences between the groups, although methodological details were not given. The subjects were asked if they were right or left footed; this was not strongly correlated with the DT result. The researchers found that 35% of the dyslexic group had suffered mild birth trauma and 33% had a "genetic trait", which they suggested could lead to abnormal cerebral lateralisation. No equivalent data were given for the controls and these figures were not related to DT results. The authors speculated that the lack of stable motor ocular dominance may cause abnormal eye movements. They concluded that the DT "is a reliable and objective method of diagnosing 'visual' dyslexia."

Fowler and Stein (1983) believed that up to 50% of dyslexic children had "visual dyslexia", which manifested as unstable dominance with the DT. They described 5 cases of alternating esotropia, which they thought may have resulted from a difficulty in achieving dominance. These were "cured" by occlusion of the squinting eye; a corresponding improvement in reading and writing was also reported. They suggested that hysterical amblyopia may be caused by unstable dominance and that anisometropia decreased the probability of dyslexia occurring. They thought that occlusion therapy for strabismus could cause dyslexia and that alternating strabismus may, for similar reasons, be undesirable.

Stein and Fowler (1984) stated that eye movements, including vergence, were probably predominantly controlled in the right hemisphere, whilst reading depended on the left inferior parietal lobule and angular gyrus. They believed, like Dunlop and Dunlop (1974), that retinal and eye position signals corresponding to objects seen with the central region of the visual field were represented in both hemispheres. They thought that, because of homotopic connections between these representations, information that was transferred from one side of the brain to the other was liable to be mirror reversed. The development of a stable leading eye was thought to help resolve the confusions engendered by binocular convergence, bilateral representation of the maculae, and homotopic interhemispheric communication. They stated that this "central region" with bilateral representation subtended 5-10° (c.f., Dunlop, 1976). Fowler et al. (1985) gave a brief precis of their research to date.

Newman et al. (1985) examined 298 children who were aged between 7 and 11 years. This sample came from several schools and, unlike that of Stein and Fowler (1982), had not been referred to any clinic for reading difficulties. Children with a verbal or performance IQ less than 90 were excluded and the DT was used in the same way as Stein and Fowler (1985). Newman et al. (1985) did not find any association between the DT results and spelling, reading single words, or reading prose passages. They classified subjects with a reading retardation of 18 months or more as dyslexic; they did not give any data on the intelligence of this group. "Unfixed dominance" was as common in the dyslexic group (about 53%) as in good readers. They suggested that this could be explained by different referral criteria or because, in Stein and Fowler's (1982) study: "It appears that the testing was performed on different occasions and thus it is unlikely that it was performed blind."

Bigelow and Mc Kenzie (1985) investigated a causal relationship between the DT result and dyslexia by comparing 2 groups who were matched for reading age. Both groups contained 9 boys and 5 girls and had similar intelligence (the mean IQ of the control group was 4 points higher); the mean age of the dyslexic and control groups were 10 and 8 years respectively. The reference eye was assessed using a tranaglyph where the subject viewed, through coloured goggles, 2 slides with different coloured monocular markers. The slides were manually moved apart until a fixation disparity was induced. The authors failed to describe the following important details: whether the eyes were diverged or converged; the working distance; the size of the slides; and the angular separation of the monocular markers. They also assessed the reading age and, tachistoscopically, the children's ability to match reversible letters and symbols. They found that few errors were made with this last task, and that the number of errors and time taken were not significantly correlated with reading ability. The reading ability was significantly inversely correlated with unstable ocular dominance, both using the pass criteria of same reference eye for more than 8 out of 10 trials ($p < 0.05$) and by measuring the degree of ocular stability using a discrete interval scale ($p < 0.01$). The testing was repeated after 14 weeks and the results were found to be 92% reliable. The researchers concluded that unstable ocular dominance was a correlate of dyslexia, but that a causal link had not been demonstrated. Advantages of this study were that it further investigated the relevance of the DT with reading age-matched groups, different apparatus, and an assessment of reliability; but it unfortunately suffered from lack of detail and limited subject numbers.

Stein and Fowler (1985) investigated the treatment, by occlusion, of the "visual dyslexia" that they identified with the DT. The subjects were 201 children who had been referred to an ophthalmology department by GP's, school medical officers, and primary school teachers. Dyslexia was diagnosed when reading performance (BAS) were more than 1.96 standard deviations below that expected from the scores in the similarities or matrices subtests of the BAS. A reading specialist categorised the children's spelling errors as visual or phonemic. A full medical history was taken and the children were given an ophthalmological and orthoptic assessment, including the DT. Details of these examinations and results were not given, although the children were said to be free of overt ophthalmological, neurological, medical, or psychiatric conditions. Half the consenting children were randomly allocated occluding spectacles and the other half received clear plano glasses. After 6 months the glasses were removed from those subjects whose reference had become or remained fixed. All children who still had unfixed reference were then given occluded spectacles and this procedure was repeated after another 6 months.

Stein and Fowler (1985) found that 148 of the 201 children met their diagnostic criteria for dyslexia. Most of the dyslexic group (84%) were male, 56% had had birth complications, and 57% had a family history of dyslexia. There was a slight link between visual-type spelling errors and "visual dyslexia", but this failed to reach significance. During the first 6 months, significantly more of the unfixed reference group became fixed if they wore occluded spectacles than if they wore plain spectacles ($p < 0.01$). The reading ability of those who became fixed showed a more rapid improvement than that those who did not ($p < 0.005$). A sub-sample of 20 pairs of children was selected; the pairs were matched for initial IQ and degree of reading retardation. One of each of these pairs had received placebo spectacles and remained unfixed and the other had received occlusion and became fixed. The latter group made much better reading progress. This was the case for all IQ levels, although it was greatest for those with highest IQs.

It is unfortunate that the subject's age was not accounted for in the statistical analysis, since Stein et al. (1986) found this had a major effect on the DT results. Stein and Fowler (1985) only assessed the intelligence at the initial assessment and, therefore, they did not know if some of the subjects underwent a phase of rapid general development during the study. This could have resulted in subjects with an initial developmental lag, which may have manifested as unfixed reference, developing a more stable reference eye and improved reading performance. Stein and Fowler (1985) concluded that approximately one third of dyslexic children had fixed reference (their dyslexia was caused by phonemic problems), one third had visuomotor problems that were helped by monocular occlusion, and one third had visual and phonemic problems. They thought that the reading of the latter group may not improve, even if the reference eye became fixed.

Franklin (1985, unpublished) reported the observation that the eye in which a fixation disparity occurred may vary with the fixation distance and elevation or depression of the eyes. Although the influence of head position on the size of fixation disparity was investigated by McKee et al. (1987), they did not note the effect on the consistency with which one eye maintained fixation. Franklin's (1985, unpublished) hypothesis to explain the Stein and Fowler's (1985) results was discussed in Section 2.4.

Stein et al. (1986) repeated Newman et al.'s (1985) study. They examined 753 children, aged 5-11 years, from 11 primary schools. Data on the reading performance of 451 of the children were available from various tests that had been carried out by teachers; and IQ data were also available for some of the children. The researchers were unaware of this information when carrying out the DT. The results supported their previous studies, in contrast to those of Newman et al. (1985). For example, Stein et al. (1986) found that children who had achieved stable reference were a mean of 6.3 months more advanced in reading than those without stable control. The incidence of a stability increased with age: 52% of 5-6 year olds had stable responses, compared with nearly 90% of 10-11 year olds. The researchers commented that: "We have only just begun to appreciate the unreliability of this test in inexperienced hands."

Holland (1986) analysed the eye examination results from 169 children who were aged 5-16 years. He assessed ocular dominance using a polarised technique; no more details were given, although he probably used a near Mallett Unit to assess the eye in which a fixation disparity occurred. A "suspect group", comprising 31% of the sample, were felt by parents or teachers to have difficulties with reading. The author found that 37% of the suspect group had undecided eye control, compared with 14% of the total sample. This study was criticised in Section 2.3.3.

Aasved (1987), in a study that was described in Section 2.4, carried out the DT on 117 dyslexic pupils (no diagnostic criteria were given) and 89 "comparable control" children (no details of these children, or any matching criteria, were given). The test was repeated 10 times, and on 2 separate occasions; since this is the only report in the literature of an assessment of the test-retest reliability of the synoptophore DT it is regrettable that these data were not included in the paper. The results were described as normal, crossed, or unstable dominance, or suppression. Although a slightly higher proportion of the dyslexic group demonstrated unstable dominance or suppression, these data were said to be "very much the same". The dyslexic group were also classified into different dyslexia subtypes (*see* Section 2.4; no significant differences between the DT results for these subgroups was found. The author concluded that there was no scientific basis for treatment of any kind of dyslexia by occlusion.

Masters (1988) described her orthoptic management of 239 cases of dyslexia, which was based on that of Stein and Fowler (1985). Dyslexia was "diagnosed" by an educational psychologist or remedial teacher (no criteria were given). She said that several conditions were more common in dyslexia: abnormal saccades, poor accommodation and convergence, unstable reference, and worse foveal than parafoveal convergence. No data or statistical analyses were given to support these contentions. It was noted, paradoxically, that an eye that was being occluded may develop as the referent eye. She classified approximately 45% of her sample as "visual dyslexics" and treatments included physiotherapy, dietetic advice, orthoptic exercises, and occlusion. The effect of treatment of 63 visual dyslexics was described as follows: 67% were "cured", 13% unchanged, and 21% did not attend.

Stein et al.'s (1988) investigated the relationship between the DT result and vergence responses (fusional reserves). They used a limbal reflection device to record eye movements during forced (ramp) vergence to 2 different sized targets (2.5° and 7.5°) in a synoptophore. Their subjects were 39 dyslexic children, aged 8-11 years, and 24 age- and sex-matched controls. A "blind" protocol does not appear to have been adopted for the DT or for the analysis of the eye movement traces. The selection criterion for the dyslexic group was a reading age more than 2 standard deviations behind the performance IQ. Although all the children had been referred to a hospital orthoptic department it was stated that none of the dyslexic children had any ophthalmological conditions; it was not clear whether this statement also applied to the controls.

They found that 24 of the dyslexic children had unstable dominance ("unfixed"). Analysis of the eye movement recordings for the 2.5° targets showed that the control group converged by a mean of 6.5° (SE 1.3°) and diverged by 2.4° (SE 0.3°) compared with 3.3° (SE 1.8°) and 0.3° (SE 0.3°) respectively for the unfixed dyslexic group. The 14 dyslexic children with fixed reference showed the same vergence responses as the normal group (the data were not given). With the 7° fusion targets the differences between the groups were much less pronounced. The researchers pointed out that the usual convergence stimuli in eye examinations (such as the RAF rule) were nearer 7° in size than 2.5°; this may explain some of the controversy in the literature. They did not explain the relevance of their findings to reading, when adjacent letters and words provide a far larger fusional stimulus than their 7° target. The authors erroneously stated that the smallest synoptophore slides of the DT houses subtended 2.5°; in fact they subtend 3.5° (Clement Clarke International Ltd., 1989). The 7° fusion targets were not described in the paper. The authors believed that, for fine vergence control, the monocular macula signals had to be distinguishable so that those from each eye could be used to guide the movements of that eye. They hypothesised that this was not possible for dyslexic children with unstable reference and that this could be corrected by occlusion therapy. Eames (1934) also found decreased fusional reserves, particularly to small targets, in dyslexia (*see* Section 2.4).

Fowler et al. (1988), in their first experiment, investigated the effect of target size on the vergence response of 39 normal children, aged 9 years. They carried out the DT and measured the amplitude of convergence in the synoptophore with 7°, 3°,and 1° targets. The amplitude of convergence increased with target size and only correlated significantly with the stability of response on the DT for the smallest target size. This correlation was, however, better for the 7° target ($p < 0.12$) than for the 2° target ($p < 0.20$). The authors' second experiment studied the effect of vergence stimulus speed on 19 dyslexic and 28 control children, aged 9 years. The DT was carried out and the amplitude of convergence was measured in response to 2° targets moving at 0.3, 0.6, 1.0, and 1.4 °/s. The amplitude of convergence increased as the speed reduced and the results best correlated with the stability of response on the DT for a speed of 0.6°/s. The authors did not give any selection criteria and used the term "the range of vergence" to describe positive vergences (positive fusional reserves). This study also lacked any assessment of the subject's intelligence; it has been shown that this is a major confounding variable in DT performance (Bishop et al., 1979; Bishop, 1989).

Fowler et al. (1988) assumed that the positive vergences were correlated with the DT, which relates to the behaviour of the eyes during divergence. Their reasoning for this seems to have been that both tests required the subjects to make proper use of retinal disparity signals. This argument would be appropriate for tests in which a convergent or divergent fixation disparity was induced. It is difficult, however, to find a connection between vergence amplitude to a ramp stimulus and an inability to make use of retinal disparity signals; if the subject could not make use of retinal disparity signals then they would not be able to start to converge when the stimulus was first altered. The only feasible connection with the DT is that , if one assumes a motor resistance to convergence, then the degree of retinal disparity may increase as the convergence of the tubes increases. This would result in an increasing amount of crossed disparity, in contrast to the uncrossed disparity which was induced in the DT.

Yule (1988) briefly reviewed recent work using the DT. He felt that dyslexia, although heterogeneous, resulted more from a language difficulty than from a visuomotor problem. He advised general medical practitioners to simply check the V/A of dyslexic children; this was shown in Chapter 2 to be a relatively irrelevant and unproductive investigation. Stein (1988), in a reply to Yule (1988), re-iterated his belief that visuomotor deficits were more important than language disorders in dyslexia.

Riddell et al. (1988a) presented a brief summary and update of their research. They described a computerised method of assessing the accuracy of children's direction sense. They had linked inaccurate direction sense with poor vergence control (this seemed to describe an unstable response on the DT) and were planning to correlate this with reading ability. They also mentioned a 4 year longitudinal study of vergence control. This was said to increase with age, but lead to RD if still poor by the age of 7-8 years.

An abstract by Riddell et al. (1988b) described a study of 74 dyslexic children and 80 controls, who were matched for chronological age. The vergence eye movements to small targets were recorded, and the stereopsis was measured (with the Randot Test). Twenty of the dyslexic children were matched by IQ and reading age with 20 younger normal readers. The dyslexic children demonstrated significantly worse control of their vergence eye movements and poorer stereoacuity. The authors concluded that a visuomotor disorder was one cause of RD.

Bishop (1989) reviewed recent theories and research relating to the DT. She questioned the link between unfixed reference and reading ability, which had not been found by Bishop et al. (1979) or Newman et al. (1985). She proposed that this discrepancy could be explained by the effect of chronological and mental age on DT performance. She noted that many good readers had unfixed reference on the DT (24% in the study by Stein et al., 1986). Bishop (1989) questioned the theoretical link between the DT and dyslexia on 2 grounds. Firstly, she hypothesised that motor immaturity (manifested as unfixed reference) and delayed language development were indicatory of a single underlying cause, such as delay of neurological maturation. Secondly, she pointed out that attentional disorders associated with dyslexia disrupted performance on a range of tasks, which could include the DT. She noted that in Stein and Fowler's (1985) study a reading specialist had classified, using a blind protocol, the spelling errors made by the subjects as suggesting either a visual or auditory problem. There was no clear correlation between the type of error and the DT results. She finally questioned whether dyslexic children with unfixed reference could be helped by monocular occlusion. Several methodological errors and omissions from Stein and Fowler's (1981) and (1982) studies were given. Bishop (1989) re-analysed the raw data from Stein and Fowler's (1985) study and corrected some errors. Her re-analysis did not find a significant increase in reading ability with occlusion and showed that the correlation between a more stable reference eye and reading ability was due to differences in the initial reading ability. She concluded that there was no evidence that monocular occlusion of children with unfixed reference resulted in improved reading scores.

Stein (1989a) criticised Bishop's (1989) review. He argued that Bishop et al.'s (1979) study was weakened by matching the groups for WISC full scale instead of performance IQ. He felt that recent studies had shown conclusively that there was a strong association between unstable vergence control and poor reading. He thought that his 1985 study, contrary to Bishop's (1989) description of it, had shown that children with unstable vergence control make the kinds of visual localisation errors that his theory predicted. Concerning the improvement in reading following occlusion, he noted that Bishop (1989) had re-analysed his original data using t-scores and he criticised this technique for being too coarse. Stein (1989a) concluded that: many RD children did have binocular control abnormalities, although many of them also had phonemic segmentation difficulties. He acknowledged that the onus of proving causality lay with his team.

Stein (1989b) stated that dyslexia probably resulted from a minor disorganisation of hemispheric specialisation. He reviewed his team's research as showing that dyslexic children's symptoms of small letters blurring and moving around were associated with distorted vergence control, unstable binocular fixation, impaired visual direction sense, and reduced stereoacuity. These abnormalities were said to be characteristic of patients with lesions of the right posterior parietal cortex. He suggested that dyslexic children with unstable binocular control showed specific signs of disordered development of the right posterior parietal region. These signs included a tendency to left neglect, very inaccurate localisation of dots in the left hemifield, and marked instability of the left eye during convergent fixation. He concluded that many dyslexic children suffered disordered development of the visuomotor processing functions of the right hemisphere, and that this caused many of their reading problems. Stein (1989b) stated that the children in his DT studies had no clinically overt visual problems detected at an eye examination. It is surprising, therefore, that most of the two thirds who had unstable reference were said to fail to make any vergence movements when the synoptophore tubes were diverged. The evidence for causality was taken from the occlusion studies and the use of reading-age matched controls. He cited research suggesting anatomical abnormalities in dyslexia (Galaburda and Kemper, 1979), but did not point out that these anomalies were virtually confined to the left hemisphere.

Stein et al. (1989) reviewed their research and hypotheses. They linked the presence of an unstable response on the DT in association with decreased vergence amplitude to difficulties with the constant vergence adjustments during reading. This link, however, has not been proved experimentally. Concerning the treatment of poor vergence control, the authors preferred exercises based on physiological diplopia for children over the age of 8.5 years.

Stein et al. (1989) briefly described an experiment showing impaired vergence control to be associated with poor performance at a dot localisation task. This study would seem to have been confounded by laterality effects. Subjects with poor binocular control were also said to demonstrate erratic eye movements during this task, although this finding could be explained by attentional factors. This study also found that children with poor vergence control made many more errors when the stimulus was presented in the left visual field. This supported the authors' hypothesis that some reading problems were caused by impaired development of right hemisphere visuospatial functions.

Stein et al. (1989) thought that the most difficult task for the right posterior parietal cortex was accurate vergence control. They pointed out that right posterior cortical damage usually lead to RD and that some neurophysiological studies had found abnormalities of the right posterior parietal cortex in dyslexia. They thought it quite likely that both left and right hemisphere disorders had a common genetic/developmental/endocrine aetiology (see Section 1.5.3.1).

Liu et al. (1989) investigated the relationship between the DT result and the Boder (1971) classification of dyslexia. The DT was carried out with a Mallett Unit and rotary prisms instead of a synoptophore. The results of this test did not distinguish between dyslexic and normal readers or differentiate either of the Boder sub-groups from one another or from the controls. The importance of these findings was reduced by several methodological weaknesses; e.g., it was assumed that the Boder sub-typing was a definitive classification, the DT results were based on divergence and convergence, it seemed that the polaroid filters were not reversed throughout the trials, the Boder sub-types were not identified by conventional or rigorous means, and the selection criteria for the dyslexic group were not given.

Buckley and Robertson (1991) briefly reported the DT results of 100 learning disabled children and 100 controls, all aged 9-11 years. Using Stein and Fowler's (1981) criterion, more control children demonstrated unfixed reference than learning disabled. The majority of children had not developed a fixed reference eye. They found that the DT result was very unreliable and often changed between appointments, without any change in academic performance. They felt that the test represented a very difficult task for the child and involved an element of "guess work". They concluded that the validity of the DT in its present form was questionable.

Stein (1991a) and Fowler (1991a) briefly reviewed their research and concluded that dyslexic children demonstrated unstable binocular control, poor stereoacuity, and inaccurate judgements of visual direction. The term unstable binocular control seemed to replace previous terms such as unfixed reference and poor visuomotor control. Stein (1991a) linked these findings with a defect of the transient visual system (*see* Section 9.2.2) and, whilst still maintaining that the visual impairment was a potent cause of reading difficulties, suggested that most dyslexic people have both visuospatial and phonological problems.

Watkins (1991) criticised Stein and Fowler's research since the dyslexic children had been referred to an ophthalmological department and, therefore, would be expected to have ophthalmological problems. It is not clear to which of their studies he was referring.

Cornelissen et al. (1991a) studied 2 groups of children who were selected from a population referred for orthoptic assessment because of suspected reading difficulty. The experimental group comprised 45 children who had "failed" the DT and the control group contained 45 children who had a fixed response on this test; the groups were matched for chronological and reading age, IQ, and performance at a rhyming task, but were not matched for sex. The subjects read 3 single real word lists that were matched for linguistic complexity but that contained reducing print sizes in consecutive lists. They hypothesised that if a visual impairment was interfering with a child's reading then it would result in an increased proportion of nonword errors, particularly with the smaller print size.

All children made more errors as the print size reduced, but only the group who had failed the DT made proportionately more nonword errors as print size reduced; the interaction between DT result and print size was significant. At each print size children always made more nonword errors if they had good rather than poor phonological skills (as assessed by the rhyming task). This discrepancy was significantly more marked for children who failed the DT. This study suffered from the following weaknesses: the "performance IQ" was calculated only from the matrices and similarities T-scores from the British Ability Scales; the regression model that was used in the statistical analysis converted several continuous variables to discrete variables in only 3 groupings. A significant increase in the proportion of nonword errors in the experimental group only occurred when changing from the large (24 point) to the medium (12 point) type; the change between medium and small (9 point) print was negligible. Both the proportion of nonword errors and the likelihood of failing the DT would be increased by a child's tendency for inept guessing when faced with uncertainty over a response. Since all children made more errors as print size reduced then the increased incidence of nonword errors in the experimental group could be a consequence of their "guessing strategy". The authors concluded that their results suggested a link between the "efficiency of visual processing" and the accuracy of reading in their sample.

Cornelissen et al. (1991b) briefly presented the results of a study that had found, with small subject numbers, that subjects who failed the Dunlop Test showed significantly more variation in vergence angle during binocular fixation. He said this resulted, principally, from slow drifts.

3.3.1 Conclusions

The literature on the role of the DT in the management of dyslexia is equivocal. The DT was first developed to detect unstable motor ocular dominance; it was then used to detect crossed dominance. More recently, it has been applied, once again, to detect unstable dominance, although such results are now normally described as indicating "binocular instability". Few studies, except for those of one research team, have found an unstable response on the DT to be a correlate of dyslexia. The term binocular instability was introduced in 1938 by Cantonnet (cited by Giles, 1960, p. 465) and describes decreased vergence stability and amplitude, and sometimes increased heterophoria and poor general health or fatigue. More work is needed to confirm whether this condition is synonymous with an unstable response on the DT, although it has been claimed that the DT is better at detecting binocular instability than conventional binocular vision and orthoptic tests (Fowler, 1991b). The DT has been shown, however, to be unreliable in most hands (Stein, 1991b) and the hypothesised binocular instability must be validated with other, more reliable, measures before it is widely accepted.

3.4 General Conclusions

The literature suggested that tests of ocular dominance could be classified into those that assessed motor or sensory dominance, although there was some confusion over the classification of sighting dominance. A new, hierarchical, model of ocular dominance has been proposed, in which "pure" tests of sighting dominance have been classified as a form of sensory dominance.

There was little evidence in the literature to support the Ortonian concept of an association between crossed dominance and excessive reversals during reading and spelling, although these may be characteristic of a rare dyslexic subgroup. Dyslexia has not been convincingly shown to be associated with any kind of ocular or mixed dominance as assessed by sighting tests, although unilaterality may be associated with better reading skills in the general population. The Phi Test and tests based on retinal rivalry are both measures of sensory dominance that have been shown to have severe limitations. The evidence from experimental neurophysiology on the role of cerebral dominance and hemispheric specialisation in dyslexia is also inconclusive, and longitudinal studies including autopsy investigations may provide some answers. Most modern theories of the aetiology of dyslexia assume that there are subtle cerebral abnormalities in dyslexia. If this is the case then, bearing in mind that cerebral dominance changes with different tasks, the results of some sensitive tests of dominance might be expected to be abnormal in dyslexia.

Interest in the role of ocular dominance in dyslexia has been revived by the DT, which in its modified form can provide a measure of the stability of motor ocular dominance. The literature on the relevance of this test is equivocal and the interpretation of its result has gradually moved away from dominance towards binocular dysfunction. The test has been shown to be unreliable and, if it does detect "binocular instability", then conventional optometric tests may be more appropriate. The evidence in Section 2.4 concurs with that in Section 3.3 to suggest that some binocular vision problems are a correlate of dyslexia.

If atypical ocular dominance or binocular dysfunction are a major causative factor in dyslexia then occlusion therapy should be beneficial. The evidence for the success of this therapy is equivocal. Children who suffer from binocular vision problems may compensate by closing, covering, or moving their head to occlude one eye (Mallett, 1988; Stidwill, 1990, p. 52); these phenomena do not seem to be frequent correlates of dyslexia (unpublished observations). O'Grady (1984) described the results of questionnaires completed by the teachers of 293 unselected 7 year old children. One of the types of behaviour that was assessed by the questionnaire was whether the child often covered an eye when reading; none of the forms reported this observation.

CHAPTER 4

A REVIEW OF THE USE OF TINTED LENSES AND RELATED THERAPIES FOR THE LEARNING DISABLED

4.1 INTRODUCTION

To describe this therapy adequately it is necessary, contrary to normal practice, to review some papers that have not been published in refereed journals. These papers will be identified and comments will be made upon their methodological adequacy.

4.1.1 General Considerations on Tinted Lenses

Trevor-Roper (1974) reported that 6% of spectacles ordered in England were tinted. Borish (1975, pp. 1126-1127) summarised a report in 1953 by the Joint Committee on Industrial Ophthalmology which stated that tinted lenses may be useful from a cosmetic standpoint but should not be promoted for the relief of photophobia, "nor promulgated upon the basis of any physiologic advantages such as reducing difficulty associated with fluorescent lighting, improving the acuity, or similar claims."

Sasieni (1975) advised caution in acquiescing to a patient's request for a non-prescribed tinted lens, since a complaint of photophobia may be a sign of uncorrected ametropia. He stated that tints should not be prescribed merely as a placebo. Brooks and Borish (1979) felt that the absorptive properties of a tint that was selected primarily for the comfort of the wearer could be determined subjectively. They stressed, however, that other factors should be taken into consideration, and noted that tints that were too dark could be hazardous owing to a reduction in V/A at low lighting levels. They described the properties of different coloured tints and the circumstances when they were appropriate.

Fannin and Grosvenor (1987) also cautioned that dark tints may impair vision under conditions of dim illumination, and described the properties and uses of various coloured tints. British Standard 2724 (1987) specified the maximum relative visual attenuation coefficient for each of 4 signal colours that was permitted for general use sunglare filters. This highlighted the danger that might result from highly saturated tinted lenses when trying to identify traffic signals.

Trevor-Roper (1974) suggested that some individuals wore tinted glasses due to neuroses. Howard and Valori (1989) investigated this experimentally by comparing the personalities of 20 hospital patients who wore tinted spectacles with those of 20 controls who were matched for age, sex, and diagnosis. The former group exhibited a significantly higher level of psychopathology and the authors concluded that the wearing of tinted spectacles was a valid indicator of psychological distress among hospital patients.

4.2 IRLEN LENSES

4.2.1 Historical Perspective

Critchley (1964) cited a case study by Jansky in 1958 of a dyslexic child who was unable to read words on white card, but could manage to read words printed on coloured card. Meares (1980) suggested that some children's perception of text and reading disabilities were influenced by print characteristics. She found that in some cases the white gaps between the words and lines masked the print and caused anomalous visual effects, such as the words blurring, doubling and jumping. She noted that this was helped by reducing the size of the print, using coloured paper, reducing the contrast, or using white print on black paper. She suggested that research should consider these factors.

4.2.2 Research on The Irlen Treatment

Irlen (1983, unpublished) presented a paper on the "Successful Treatment of Learning Disabilities". She described a new type of specific visual dysfunction that she called scotopic sensitivity syndrome (SSS). This was said to be a major factor in dyslexia that could be treated with tinted lenses and was described as "a dysfunction that occurs once the image has been focused on the retina". She summarised a study of 107 individuals, aged 9 to 54 years, who suffered from learning disabilities and many of whom were asthenopic. The subjects were tested using the "Irlen Differential Perceptual Schedule (IDPS)". This seems to have been a questionnaire covering 6 general categories: visual resolution, depth perception, sustained focus, span of focus, peripheral vision, and asthenopia. Those who exceeded a certain score were examined by an ophthalmologist who found "subject symptoms to be nontreatable". The subjects were prescribed "the newly developed photopic transmittance lenses" and were immediately re-administered the IDPS, and subsequently interviewed after 1 month.

The author found (presumably from the IDPS results) that many (70% of one group) of the subjects described visual symptoms that impaired their learning and that these symptoms were reduced by tinted lenses. This paper lacked detail in several important areas: subject selection criteria; the nature of the IDPS; how many subjects "failed" the IDPS; nature and results of the ophthalmological examination; and characteristics of the tinted lenses. Very little data was given, no statistical analysis was carried out, and there was no control group. These results were interpreted as supporting the existence of a previously unrecognised ocular dysfunction that impaired reading and depth perception. The author believed that the severity of SSS varied from mild asthenopia, causing a reduced reading speed, to impaired visual resolution, causing dyslexia.

Stanley (unpublished and undated) described the symptoms of SSS under the following headings: photophobia, visual resolution, sustained focus, span of focus, depth of perception, and eye strain. Some of these terms were given unconventional or potentially confusing meanings: visual resolution was defined as the difficulty of keeping an image constant; it is unclear if sustained focus was synonymous with poorly sustained accommodation; span of focus described perceptual span when reading; and depth perception was related to gross motor tasks such as parking cars or walking in a straight line (these are unlikely to be related to stereopsis). One final symptom of SSS, ocular vertigo, was not defined. The author sent questionnaires to 60 children, aged 8-16 years, who had been diagnosed as having SSS and had been prescribed Irlen tinted lenses; no other selection criteria were given. He requested that the questions were answered by teachers, parents, and the children themselves, although no details were given of the respondents or response rate. The time lapse between starting lens wear and completing the questionnaire was also unclear. All subjects found that the tints helped. This was not surprising considering that the questions were based on the IDPS, which was initially used to select the tints. Additionally, some of the questions were positively biased (e.g., has the printed page become still?, have you gained more self-confidence?, etc.). This study did not include any statistical analysis or control group. Several case studies were appended, some of which strongly suggested refractive or binocular vision problems (e.g., "Ryan liked to stand up when trying to read the words").

Stanley described a second study using the Munzert IQ test (no details were given of this test, which does not appear to be in common use; Sweetland and Keyser, 1983). The subjects (aged 16-36 years) comprised an experimental group of 10 who were diagnosed as having SSS and a control group of 10 without SSS. It was not stated whether the groups were matched for age or sex or how the control group was selected, although it seems likely that they were not learning disabled. The IQ test was administered orally to 10 subjects whilst the other 10 were given the written paper. On a second test paper (presumably of similar difficulty to the first) the procedures for the 20 were reversed. It is unclear whether the experimental and control groups were split between or respectively comprised the 2 groups. The 10 subjects with SSS had higher scores in the oral test than in the written test whilst the controls scored similarly on both tests; no other data or statistics were given. Since the children with SSS had effectively been pre-selected as having difficulty with the written word, this result hardly seems surprising, or to support the use of tinted lenses.

Whiting (1985) described the symptoms of SSS in a similar way to Stanley (*see* above) and described its diagnosis on the basis of the IDPS. He stated that function of the tinted lenses was "to admit as much as possible of the light spectrum, while excluding those parts of the spectrum that seem to be causing problems". He did not explain why the problematical part of the spectrum varied from one individual to another. He described some vague results of a survey and stated that a new treatment centre in Australia had been found that the Irlen lenses helped between 50 and 70% of learning disabled referrals. The author related the use of tints to visual information requirements during reading, but did not cite any of the research on visual information processing and reading (e.g., Lovegrove et al.; 1986a). He noted that more research was needed.

Adler and Atwood (1987, unpublished) compared an experimental group of 23 subjects with 18 controls; the subjects were described as "high school students" and adults. The selection criteria were self-enrolment in a special education program and poor performance on the IDPS. Tinted lenses were prescribed to the experimental group, but not to the controls. Some details of the IDPS were given. It seems that this was a subjective questionnaire covering the following areas: 7 questions on visual inefficiency, which identified reading errors that were visual in nature; 8 questions on eye strain, including blurred vision; energy and effort to read, which seemed to be the cumulative scores from the previous groupings; and length of sustained focus, which seems to have been an estimate by the subjects of how long they could read for. The experimental group improved significantly in all of these areas, whilst the control group did not. The experimental group also showed a significant reduction in the "visual problem areas" identified by the IDPS (photophobia, visual resolution, and span of focus). The control group data for these "visual problem areas" was incomplete. The effect of treatment was assessed further by "specific task performance". These tasks were the time to find a place on a page, timed reading, and counting boxes within a cube. The performance of the experimental group improved significantly after treatment; the control group's data were incomplete. The experimental group received treatment other than the tinted lenses, including group counselling and career guidance. Further, the control group was not given a placebo treatment; the results, therefore, could be completely explained by the placebo effect. The authors claimed that 42% of their subjects had visual problems that had not been detected by standard eye examinations, yet no details of these examinations were given.

Stuart et al. (1987) briefly cited an unpublished thesis by Miller in 1984 that showed a significant correlation between poor reading ability and SSS. They said that SSS caused visual abnormalities at all visual tasks, but that these abnormalities were distinctly different from the types of visual processing that have been studied by other psychologists.

Robinson and Miles (1987) stated that in SSS the retina was highly sensitive to certain frequencies of light and that this caused an inappropriate firing of signals to the brain resulting in distortions, particularly with high contrast print. No evidence was presented to support this theory. They investigated the immediate effect of Irlen's tinted overlays on 40 subjects, aged 9 to 74 years. The only selection criteria were that the subjects had enquired about Irlen lenses and reported difficulty with reading or academic tasks. No optometric details were presented and it was assumed, arguably, that since most subjects had received an eye examination within the last 2 years they were unlikely to have any refractive or accommodative problems. The IDPS scores were used to classify the subjects in 3 groups and to assess the effect of tinted plastic overlays. The subjects also carried out 4 timed (1 minute) visual processing tasks with 3 filters: a clear overlay, a coloured overlay "with a colour maximising visual efficiency" (no details were given), and an overlay that was randomly selected from the remaining ones. The tasks were not fully described but involved word matching and the identification of words, letters and numbers. The task and overlay combinations were randomised and the examiner was unaware of which was the preferred overlay.

The difference between mean scores across conditions was significant for each visual processing test. There were no significant differences among group means; this is important since the lowest scoring subjects on the IDPS might have been expected to have maximum improvement with the tinted lenses. The authors noted that they used the same tasks with subjects of all ages; this may have confounded their results. They anticipated that more accurately prescribed coloured lenses would yield greater short term gains and that the benefit from tinted lenses would increase with time. They did not, however, consider the placebo effect.

Winter (1987) suggested that Irlen lenses may help for several reasons: a novelty effect, a more positive attitude through attributing problems to a physical rather than mental problem, raised parent and teacher expectations, and by reducing illumination levels to help subjects with prolonged visible persistence. He assessed the performance of 20 Irlen lens wearers, after they had read for 10 minutes, with a timed visual search task. This was carried out under the following 4 conditions: with their Irlen lenses, plano clear lenses, plano grey tinted lenses, and no lenses at all. It should be noted that 19 of the subjects had a refractive correction incorporated into their Irlen lenses. The results showed a clear practice effect, with subjects performing better on subsequent trials. Subjects performed equally well, both in terms of speed and accuracy, under all experimental conditions. The subjects were led to believe that they may perform better with the "special" grey and plain lenses. This study lacked several relevant details: psychometric data; characteristics of the tinted lenses; optometric data; and details of the type of print and fluorescent lighting that was used for the search task.

Fricker (1987-1988, unpublished) investigated the immediate effect of Irlen lenses on colour vision, stereopsis, and the immediate and long-term (1 year) effect on reading ability. She also sought the opinions of parents, teachers, and the children via questionnaires. Colour vision was assessed with the Ishihara test, stereopsis with the Stereo Reindeer Test, and reading was assessed with the Gray Oral Reading Tests (speed and accuracy) and the A.C.E.R. Silent Reading Test. The subjects were 127 children, aged 7-14 years, who were referred from many agencies, including ophthalmologists. They were estimated to have normal intelligence and had all received a recent eye examination. The subjects exhibited the normal sex ratio for dyslexia: 70% were boys. There was a normal incidence of colour vision defects (6% of boys and no girls). Less than maximal stereopsis was found in 75% of the children, and 80% of these improved with the Irlen lenses. There was a significant immediate and sustained improvement in reading speed and accuracy with the tinted lenses.

It seemed that the IDPS was originally administered to a larger group who were prescribed the Irlen lenses; the 127 in this study appeared to be those members of that larger group who returned after 1 year. This represented a major bias since the children who returned would be more likely to be "successful wearers" of the lenses. The questionnaires were continued for 3 years, but the group sizes reduced with time so that by the end of the third year only 20 parents responded. Clearly, these were more likely to represent successful wearers. The author commented that in the later years of the survey there was a reduction in headaches and asthma and an improvement in behaviour. This finding in a group of ageing children was meaningless without control data. An inevitable weakness of the study design was that only children who were willing to wear the glasses participated, and hence the subjects were self-selected as those who thought they were receiving a benefit from the lenses. Similar motivational effects arose from the fact that the parents were willing to purchase the lenses, and parents and children had to state a willingness to return for follow up and to complete questionnaires. Other weaknesses included the following: the lack of a control group; the use subjective testing without a blind protocol, the use of "loaded" questions in the questionnaire; a referral bias; and the lack of optometric and intelligence data. Despite these limitations, the stereopsis and reading results warrant further investigation.

Whiting (1988) said that photophobia occurred in SSS because the high contrast of black print on white paper caused visual distortions. He noted that some individuals with SSS compensated by altering their distance from the page (*see* Section 4.4.2). He sent a questionnaire to 343 Irlen lens wearers; 52% did not answer, and 6.4% were not enthusiastic users. The main areas of improvement with the tints were: eye-strain, visual confusions, poor visual tracking, attention, comprehension, fluency, and reading difficulty. The subjects were self-selected as potential Irlen lens wearers and, therefore, were highly motivated (the cost of the lenses was not given).

Gregg (1988) investigated 17 children who were referred by a local dyslexia society; no other subject details were given. These were screened with the following tests: retinoscopy, V/A, cover test, stereopsis (Lang), colour vision (Ishihara), and sighting ocular dominance. The children viewed print through 7 overlays (blue, green, yellow, orange, rose, purple, and lilac) and, by repeated comparisons, chose the filter that made the print easiest to see. The strength of preference for the filters was subjectively graded. Reading ability was assessed initially and later through the preferred filter. The results, which were not analysed statistically, showed that only one of the children did not state some preference for reading with a filter. Of the 10 children with a strong or medium filter preference, 80% went on to show a marked reading improvement, whilst none of those showing a weak preference improved. This study did not include a control group, the placebo effect was not considered, and some of the visual tests were relatively insensitive.

Moseley (1988, unpublished) analysed the spectral absorption characteristics of several Irlen overlays and one pair of blue Irlen lenses. He found, contrary to the claims of the Irlen Institute, "no evidence that specific wavelengths are cut out" and thought that the overwhelming effect of the filters was as an overall absorber of visible light. He briefly described a small experiment in which 28 "severely dyslexic" (few details were given) children read with and without grey tinted lenses. There were no significant differences in the mean performance with or without the lenses, although there were some idiosyncratic preferences for either condition. He felt that the Irlen Institute's statements were misleading and inaccurate, that more research was needed, and that a powerful placebo effect was responsible for most of the effects that had been recorded.

Warnock et al. (1988) briefly described a study in which they had administered an adapted IDPS to 50 learning disabled and 60 control children; diagnostic criteria for the learning disabilities were not given. They assessed the groups' preferences for tinted lenses and the learning disabled children who showed a preference were given the appropriate tinted spectacles. The subjects' reading performance was checked before and after a trial period of about 8 weeks. They found that 9.3% of the experimental and 10% of the control group met the IDPS criteria that were said to indicate a good response to tinted lenses. A tinted lens preference was found in 87% of the experimental and 37% of the control group. The 27 children who were prescribed tinted lenses showed an improved reading performance that was of borderline significance. The researchers concluded that the IDPS was not a useful screening test and that the proponents of tinted lenses needed to provide convincing evidence of their effectiveness.

Saint-John and White (1988) compared 11 dyslexic with 11 control children, none of whom wore glasses. No optometric data was given and the groups were not sex-matched. The mean age and non-verbal IQ of the 2 groups were similar, but the dyslexic group were a mean of 3 years retarded in reading; no individual selection criteria were given. The subjects were assessed for speed and accuracy whilst they read 3 (loosely) matched passages. They selected a coloured overlay from 6 alternatives (few details of these were given) and re-read the passages under 3 conditions: through the transparency; with polaroid lenses, and wearing frames without any lenses. The subjects also carried out a letter identification task, under the same 3 conditions. In this task a letter was presented for 0.15 s at various positions in the visual field; the letter was laterally and subsequently backwardly masked. The authors found that, when the whole group was considered together, their reading performance was similar under the 3 conditions. The transparencies did not improve the dyslexic group's performance any more than that of the controls. The 2 groups performed similarly at the letter identification task and the results for the peripheral region (11.4°) of the visual field were similar to those for the central region (3.8°). Neither group performed better at this task with coloured lenses or overlays.

The authors concluded that their results challenged the Irlen therapy, although they acknowledged that their sample size was small and that they did not use a wide range of colours. The placebo effect was reduced in this study because the subjects were neither self-selected nor led to believe that the coloured transparencies would help their reading. The subjects improved at the reading test on the second attempt (with tints), although by a similar amount in both groups. This practice effect could, without adequate controls, have been incorrectly interpreted as demonstrating a positive effect from tints.

Chan and Robinson (1989) investigated the effect of tinted lenses on the ability of RD children to benefit from new teaching methods (explicit instruction in comprehension monitoring). They compared a group of 20 disabled readers who had used tinted lenses for at least 6 months with 2 control groups (each of 20 children), one who was matched for reading age and another who was matched for chronological age. These groups were not matched for sex or intelligence, and the degree of reading retardation was not known. A fourth group of 20 RD children who did not wear tinted lenses were included, but their age and reading performance were not matched with the tinted lens group. The subjects read 4 matched test passages, some of which contained textual inconsistencies, and answered multiple choice questions on each passage. The subjects were randomly assigned to either a general or a specific instruction condition. In the former, they were simply instructed to look for inconsistency; the latter group were told how to monitor text for inconsistencies and how to use appropriate evaluative standards for judgement.

Statistically significant findings showed that the tinted lens group had surpassed the control group of disabled readers, but had not quite reached the level of average readers of the same chronological age. The tinted lens group differed from the disabled readers without tints in not requiring specific instruction in the use of evaluative standards (these findings may be negated by the lack of appropriate matching). The authors concluded that the tints may have reduced visual distortions, allowing disabled readers to allocate their limited working memory for more efficient textual processing. They suggested, alternatively, that a reduction in visual distortion may "have promoted a tangible expectation that renewed effort will be worthwhile." They did not consider the possibility that a placebo effect could have caused this tangible expectation.

Gole et al. (1989) studied 24 children aged 9-12 years who had been referred to a multi-disciplinary group that provided assessment for dyslexia. The main selection criteria were: IQ over 85, verbal IQ over 90, and reading age more than 2 years behind chronological age. The intelligence test was not named and no eye examination (other than unaided vision) was carried out. The children were randomly assigned to an experimental (13 individuals) and a control group; these groups were matched for age and intelligence. In the first stage of the study all the subjects viewed print through 6 variously coloured overlays (under constant lighting conditions) and reported which of the tints, if any, improved the legibility of the material. Secondly, tinted lenses were selected by the experimental group with an optometrist who was unaware of the choice of overlay. The lenses were selected on the basis of positive responses while viewing text; in the absence of such responses plano clear lenses were prescribed (it is not clear for how many children this was the case). The trial tints were red, green, yellow, or blue standard ophthalmic tints in "densities" of 15%, 25%, 35%, 50%, and 75%. After 1 school term the third stage of the study took place when the original control group was fitted with tinted lenses. The change in reading performance of the 2 groups after the first term was not significantly different. When the control group was fitted with glasses, there was no difference in the change of reading age over the next term for those with or without glasses. There was no clear correlation between the choice of coloured overlay and tinted glasses (see Wilkins and Neary, 1991). Only 11 of the 24 children were still wearing their tinted lenses at the end of the second term, and 3 of these had clear lenses.

The original sample comprised 381 children; the majority were excluded for medical, pragmatic (e.g., travelling distance too great), or ophthalmic (spectacle wearers) reasons. The most significant medical reason was that 54% of the sample suffered from asthma; they were excluded because of possible neurological effects of the condition or medication. This incidence was higher than the normal rate (20%) and may be related to Geschwind's theory of the aetiology of dyslexia (*see* Section 1.5.3.1). It is possible that the excluded children may have constituted a sub-group who benefited from tinted lenses. The authors thought that the double spacing of the Neale Analysis of Reading Ability may have increased legibility and obscured the effect of the tints (*see* Section 4.4.2). They concluded that any benefit from Irlen lenses was at most marginal in non-asthmatic dyslexic children. They stated, however, that: "Our own experience with over 1200 children who have been fitted with tinted lenses indicates that there is a sub-group which appears to derive considerable benefit from the prescription of tinted lenses". No data on the characteristics of this group were given. This paper included an ethical statement that the organisation responsible for the research had no commercial interest in the subject under investigation.

Hannell et al. (1989) described case reports of 2 brothers (aged 9 and 12 years) who were both more than 3 years retarded in reading and had "at least average intelligence" (no details were given). The children chose coloured overlays from a large range of colours and tinted spectacle lenses from several densities of red, green, yellow, or blue standard ophthalmic tints; colours with a bi-modal visible transmission curve were not used, although such colours (e.g., purple) are frequently used by the Irlen Institute (Wilkins and Neary, 1991). Two independent observers optometrically investigated both children, including photopic and scotopic electroretinography and pattern evoked responses (with and without tints). An analysis of reading with and without overlays was carried out with the Neale Analysis of Reading Ability, which was modified to avoid coloured paper and double spacing. The authors also assessed the performance with and without tinted lenses at other subjective measures: copywriting, pattern copying, perceptions of spaces between words, and figure ground discrimination.

Both of the subjects chose dark blue overlays and tints and performed significantly better with these at all of the subjective tests, including reading. The V/A of both children improved with the tints (for subject 1 from 6/18 to 6/5), as did the stereopsis with subject 2 (from 400" to 80") and colour vision (Ishihara) with subject 1. The electrophysiological results did not appear to be abnormal or to differ significantly with the tints. The authors concluded that tinted lenses may be a legitimate treatment for visual perceptual problems in reading difficulties. Many of the subjective test results were, however, incredible and may suggest that the tints were simply working as a strong placebo. The electrophysiological results did not seem to support the authors' theory that the tints achieved a beneficial effect by modulating the transmission of information from the environment to the visual cortex. This paper demonstrated that an effect similar to that reported by the Irlen Institute can be obtained using standard ophthalmic tints.

Scheiman et al. (1990) described 3 adults who wanted to undergo the Irlen therapy. Their symptoms, which included eyestrain, diplopia, difficulty concentrating on reading, and photophobia, were typical of Irlen candidates. Two of the three were found to have binocular vision problems (mainly poor convergence) and the third had uncorrected anisometropia (secondary to radial keratotomy) and associated anisophoria. They all responded well to conventional therapies (vision training and spectacles) and symptoms were resolved so that the patients no longer desired to be fitted with tinted spectacles.

Grisham et al. (1990) investigated the reading efficiency of 35 RD adults under the following conditions: no lenses, placebo lenses (anti-reflective coatings), neutral density lenses, and preferred tinted lenses. Optometric data, including eye movement recordings, were collected and a symptoms survey was administered. The eye movements were slightly more efficient with coloured lenses, but no faster, and 94% of the subjects had unresolved binocular vision deficiencies. Their results were said to demonstrate a strong placebo effect, although this brief abstract gave did not give any data or statistical analyses.

O'Connor et al. (1990) used the IDPS to classify 92 RD children as "scotopic" or "nonscotopic". The subjects were randomly assigned to 1 of 6 groups using coloured or clear overlays. The reading performance improved significantly when the "scotopic" children read with the preferred coloured overlay relative to clear or non-preferred overlays. "Nonscotopic" children showed no change. This study suffered from several methodological inadequacies: there was probably a referral bias; the groups were not matched for intelligence; the improvement in reading was equivocal; and the use of age scores for the statistical analysis of reading performance may have been questionable (Solan, 1990).

Blaksey et al. (1990) investigated 30 subjects who were aged between 9 and 51 years and had requested information concerning the Irlen therapy. They were randomly placed in either an Irlen filter treatment group, a vision therapy treatment group, or a control group that did not receive any intervention; the first 2 groups each contained 11 subjects and the last contained 8. The subjects received the following testing before and after treatment: optometric examination, reading tests, intelligence tests, IDPS, and a symptom questionnaire. Both therapy groups were more comfortable after treatment, although only the vision therapy group showed improvement in "vision functioning". Neither treatment resulted in a statistically significant improvement in reading comprehension. The vision therapy group showed a significant improvement in oral reading and the Irlen lens subjects were able to read a series of words more rapidly. A small subgroup appeared to achieve maximal comfort from a combination of vision therapy and Irlen filters. It would be interesting to repeat this pilot study with more subjects.

Robinson and Conway (1990) studied 44 RD subjects (33 males), aged 9-16 years, who had been provided with Irlen lenses. The Student's Perception of Ability Scale showed a significant improvement in attitude to school and to basic academic skills at 6 and 12 months after the lenses were prescribed. There was also a significant improvement in reading comprehension and accuracy, but not in the rate of reading, at 3, 6, and 12 month intervals after the lenses were fitted. These researchers reproduced the Neale Analysis of Reading test sheets on white paper, but did not seem to change the line spacing. This study suffered from several deficiencies: no optometric test results were given (although all subjects had recently received an eye examination); the improvement in reading age was not unexpected considering that the children were ageing; and there was likely to be a learning effect with repeated applications of the Neale test (Solan, 1990). A control group was not included, although placebo lenses were worn for a 3 month period. There was a greater improvement in reading comprehension with the placebo lenses over this period than with the correctly prescribed Irlen lenses over the subsequent period.

Wilkins and Neary (1991) explained that a colour preference for overlays may be different to that for spectacles because the overlay absorbed light twice. Further, the perception of colour was different for an overlay because objects whose colour was not influenced by the tint were clearly visible, whereas with spectacles all objects in the field of view were seen through the tint. They investigated the effect of tinted glasses on 20 individuals who had been referred by the Irlen Institute. They had all been using their Irlen lenses for at least 3 months and 17 were male, 19 were aged 7-18 years, and the other was 41 years old. Most of the subjects had been described as "dyslexic". The optometric examination included the following: history, V/A, amplitude of accommodation, NPC, retinoscopy, subjective refraction, Maddox Rod, Maddox Wing, associated heterophoria (Mallett) at near, stereopsis (Titmus), colour vision (City University), and contrast sensitivity (Cambridge Gratings).

Additional questions were asked concerning handedness, headaches, and eyestrain. The subjects were tested with Cambridge low contrast gratings and a specially constructed near V/A test, both with Irlen lenses and with neutral density filters of similar photopic transmittance (individually matched). The susceptibility to anomalous visual effects was assessed while the subject wore either Irlen filters, neutral density filters, or untinted refractive correction. For this test, the subject viewed high contrast square-wave gratings of spatial frequency 3 cycles/° for 5 seconds, and then answered questions about any illusions they had seen in the pattern. This technique was thought to measure a person's susceptibility to eye-strain and headaches from patterns that may produce an over-stimulation of the visual cortex (*see* Section 4.4.2). The subjects also carried out a visual search task under the same 3 viewing conditions. For subjects with an exophoria over 4 Δ, an esophoria, or a fixation disparity, the muscle balance tests were repeated when wearing their Irlen filters. Finally, the spectral properties of the Irlen lenses were measured.

The absence of a control group renders some of the results difficult to interpret, particularly those concerning the incidence of headaches and eye-strain. Further, some of the optometric results exhibited a ceiling effect. For example, the NPC of 18 of the 20 subjects was recorded as less than 10 cm, and V/As better than 6/6 were not recorded. The amplitude of accommodation was reduced in 8 subjects. This measurement, however, was not related to their age and it seems that 5 of these actually possessed normal accommodation but gave an atypically low reading because a refractive error had not been corrected. Five of the subjects had a history of binocular vision problems. The binocular contrast sensitivity with Irlen lenses was similar to that with neutral density filters. Significantly fewer anomalous visual effects (illusions) were reported on viewing the grating patterns through Irlen lenses than with neutral density filters or untinted refraction lenses. The visual search task was performed significantly quicker with the Irlen lenses than under the other 2 conditions. There was an idiosyncratic effect of the Irlen lenses on ocular muscle balance, which did not seem to be attributable to the effects of chromatic aberration. The colour of the tints did not seem to correlate with the refractive error. Although the photopic transmittance of the lenses varied considerably, all had high transmission above 650 nm and the majority had a minimum transmission in the range 500-550 nm.

Ten subjects returned for further testing after one year. Each subject carried out the Maddox Wing and Mallett tests under at least 3 of the following conditions: with Irlen lenses, with neutral density filters, with no lenses, and with refractive correction only. A colour mixing experiment was performed in which the subjects adjusted the spectral properties of light illuminating printed text and then square-wave gratings (of spatial frequencies 2.8 cycles/° and 0.7 cycles/°). The subjects were instructed to mix a colour that made the text as clear, and then as comfortable, as possible. The muscle balance results were again idiosyncratic, with some subjects showing an increased and some a decreased heterophoria with Irlen lenses; it seemed that these results did not correlate well with those at the first examination. The colour co-ordinates that were chosen were similar to, but did not bear a strong relationship with, the colour co-ordinates of the Irlen tints.

Wilkins and Neary (1991) explained that the susceptibility to anomalous visual effects related to a possible theoretical explanation of a benefit from tinted lenses (*see* Section 4.4.2). They described an alternative hypothesis for such a benefit in terms of the temporal effects of light from fluorescent lamps. Normal fluorescent lamps show little pulsation at the red end of the spectrum and most of the pulsating light has a wavelength less than 550 nm. Since the majority of the Irlen tints absorbed maximally in the range 500-550 nm they should reduce the pulsation from fluorescent lights by a small amount. The authors suggested that this may be linked to a transient visual system deficit in dyslexia (*see* Section 4.4.4).

Barnard and Thomson (1991) reported a small pilot study that assessed the eye movements of 5 dyslexic and 5 control children when they made saccades to track a target, carried out a search task, and read a simple passage of text. These tasks were carried out with 4 different coloured filters. There was no overall effect of filters and no interaction between filters and group. Holland et al. (1991) presented preliminary findings suggesting that RD children who preferred to use a coloured overlay showed signs of binocular instability. Additionally, the reading eye movements became more regular with the preferred filter. They made the important observation that some Irlen overlays seemed to have a polarising effect that could confound the results of certain optometric tests. Solman et al. (1991) measured the contrast sensitivity of disabled and normal readers through several tinted filters. The results of this study are discussed in Section 4.4.4.

Wilkins (1991b) described a simple colorimeter that enabled an observer to illuminate text with light of a particular chromaticity by altering the hue and saturation, whilst keeping the illumination at about 30 cdm^{-2}. This was used by 9 children to select their preferred colour; they also, separately, selected Irlen tints in the usual way. In 8 of the cases the colorimeter setting closely resembled the colour appearance of the Irlen lenses. The author had developed 7 series of trial CR 39 tinted lenses that were dyed with progressively increasing deposition of each of 7 chemically stable dyes. The hue angles were spaced about 50° apart on a chromaticity diagram and 5 pairs of each dye were tinted to various saturations. These could be used to closely approximate any desired colour by superimposing trial lenses tinted with just 2 of the 7 dyes. The visual appearance of the colorimeter setting could, in this way, be closely approximated.

The author noted that individuals usually reported a reduction in discomfort and distortion when viewing a natural scene through the combination of lenses that matched their colorimeter setting. When the setting had a strong saturation, however, subjects often preferred this to be reduced in the lenses. He described the use of this system to successfully treat patients with several conditions: reading disabilities, asthenopia, headaches, and photo-sensitive epilepsy. Wilkins (1991b) noted that the area on a chromaticity diagram that corresponded with the optimal colour for a given subject may be quite small, but that its limits could often be defined with good repeatability.

4.2.3 Anecdotal References to The Irlen Therapy

Irlen (1985), in a US patent concerning her treatment, gave an overview of the characteristics and detection of the "Irlen syndrome" and some details on the spectral characteristics of her tinted lenses. This patent did not include a representative review of the literature, nor any reference to the use of coloured overlays. She suggested that the tints helped by absorbing those wavelengths that had a relatively greater effect on scotopic vision, yet she stated that tints from other sources that had similar spectral properties did not have the same effect. The 3 case studies she described had binocular vision problems (all had poor tracking, transient blurring, decreased stereopsis, and decreased fusional reserves) that may have accounted for their symptoms of eyestrain.

Holland (1987, 1988) suggested that tinted lenses may produce symptomatic relief of dynamic visual problems. He pointed out that "photosensitivity has for a long time been a recognised accompaniment of unstable binocular vision".

Clayton (1987) stated that SSS may be hereditary and affected 60% of people with reading difficulties and 15% of the general population. She said that SSS was often found in association with auditory difficulties, dysgraphia, hyperactivity, eye muscle imbalances, allergies, and emotional problems, but that it could not be remedied by vision training. She said that 92% of diagnosed cases of SSS could be helped. Unfortunately, neither the "many controlled double-blind studies" nor the research shortly to begin at a London teaching hospital that she referred to have yet been published. It seems hard to envisage a double-blind study of a treatment that is so obvious to a subject as brightly tinted lenses. One possibility may be to use Wilkins' (1991b) colour mixing apparatus to change the spectral power distribution of the light source whilst Irlen lens wearers viewed print through their tinted lenses.

4.2.3.1 Press Reports

There have been many press reports, normally enthusiastically supporting the Irlen treatment and sometimes quoting as yet unpublished research. Yeung and Heeney (1986) briefly described the work of Dr Murphy from Hong Kong, who had a "cure rate" of 80%.

Bald (1987) described a study of 50 children with reading difficulties; half of these were prescribed tinted lenses and the other half acted as a control group. He said the study showed immediate and statistically significant benefits to the tinted lens group in terms of reading errors, reading speed, ability to cope with glare, visual resolution, span of focus and eye strain. Few details of this study were given. Pitluk (1987) stated that extensive contrast sensitivity testing with and without Irlen tints had revealed no negative changes; he did not state whether there had been any positive changes.

Bald (1988) criticised Reeves' (1988) review (*see* Section 4.2.5) for being too critical. He agreed that there were weaknesses in some of the research on the Irlen lenses, but praised Irlen for having the courage to prefer the opinions of her clients to those of the establishment. Bald (1990a) described the work of Wilkins and Neary (1991). Bald (1990b) discussed several case studies showing that the coloured overlays improved the performance of RD children, particularly those who made errors with short words. He noted that, in his group of 30 users, yellow and green were just as popular as blue filters (c.f., Wilkins and Neary, 1991).

4.2.4 Weaknesses of The Irlen Argument

4.2.4.1 Lack of a Satisfactory Theoretical Explanation

The protagonists of the Irlen therapy have failed to give a complete explanation of the theory behind this treatment. Clayton (1987), who was the director of the Irlen Institute in London, stated that:

> "Research indicates that these individuals respond dysfunctionally to specific wavelengths of light, for those with SSS, full spectral light produces over-stimulation of the retinal receptors which, in turn can cause problems in seeing."

No references were given for this "research" and it does not seem possible that retinal receptors in a non-diseased eye with normal colour perception (Fricker, 1987-1988) would respond abnormally. The confusion was increased further by the following statement later on in the same paper, which seemed to propose a refractive mode of action: "By eliminating specific wavelengths of light, the focus is slightly shifted to produce sharper, clearer and more stable vision."

Menu (1985) found that the contrast sensitivity function of 8 normal adults was similar for red, green, or blue stimuli. In peripheral vision there was an equal attenuation of the contrast sensitivity function for all colours, and this was maximal for high spatial frequencies. There has been a case report in the literature of an individual whose contrast sensitivity was grossly altered for different coloured stimuli (Hyvarinen and Rovamo, 1981; and Rovamo et al., 1982). This patient, however, had severe pathological conditions (diabetes, epilepsy, and hemianopia).

Fricker (1987-1988, unpublished) suggested that Irlen tints may improve visual performance by shortening iconic persistence, which may be abnormally long in some cases of dyslexia (Høien, 1982). She did not suggest how this theory could explain the proposed specific idiosyncratic preference for certain tints.

4.2.4.2 Nomenclature

Much of the nomenclature used by the Irlen Institute seems designed more to impress the lay public than to provide useful descriptive information. For example, the use of the terms "photopic transmittance lenses" (Irlen, 1983) and "spectrally modified prescription lenses" (Irlen Institute correspondence, on file) for items that would usually be described as tinted lenses or coloured overlays seems unwarranted. SSS was defined by Irlen and Lass (1989) as "a perceptual dysfunction which is related to difficulties with light source, luminance, intensity, wavelength, and colour contrast". Whiting (1985) said that "this name was chosen because of the assumption that there was some retinal defect responsible for this extreme sensitivity to certain kinds of light".

The word scotopic relates to the power of the eye to adjust itself for seeing in the dark (MacNalty, 1963), and scotopic vision has been defined as vision at levels of luminance below about 10^{-3} cdm^{-2} and resulting from the functioning of rods (Millodot, 1986). The scotopic sensitivity curve represents the thresholds of the rods for different wavelengths of light (Davson, 1972; p. 192), and rods may be saturated at normal daylight levels of illumination (Weale, 1982). There is a group of diseases, called stationary night blindness, that are characterised by a loss of scotopic sensitivity (Sharp et al., 1990). There is no evidence to suggest that an opposite type of disorder occurs due to excessive scotopic sensitivity. Kelly (1990), however, concluded from a series of experiments that rod signals were involved in the subjective enhancement of brightness by yellow tinted lenses. This raises the faint possibility that SSS may not be a misnomer, (*see* Section 4.4.4.2), although much more evidence would be needed to support this contention.

4.2.4.3 Symptomatology

SSS seems to be diagnosed mainly on the basis of symptoms (Irlen, 1983), most of which are vague and could be the result of many other causes. For example, one such symptom is discomfort in or around the eyes; over 40 possible causes for this were listed by Ball (1982; p.109).

4.2.4.4 Specificity of tints

There is no published evidence for the claim that each individual must have a highly specific tint, and the fact that the Irlen Institute advocates the use of coloured overlays combined from a range of 7 (Fitzmorris, 1991) may further detract from this claim. When Whiting (1985) described how the Irlen Institute had evolved from using coloured paper to overlays to tints the rationale behind this was given as subject convenience rather than increasing specificity. Even less tenable are the claims that these tinted lenses can only be supplied by the Irlen Institute (at considerable expense). The director of the Irlen Institute in the UK stated that: "I would not expect that a tint made up here on the basis of a perfect visible match to the Irlen tints would be the same" (Clayton, 1989). The normal method of colouring plastic lenses is to dip them in warmed organic dyes. Several different tints can be applied to obtain the desired colour and transmission (Borish, 1975). This method is used routinely by manufacturing opticians to obtain a perfect visible match with an existing tint. If this match was obtained under daylight it seems unlikely that metamerism could result in colours that were different enough to result in widely different physiological effects. This would be a simple matter to investigate experimentally, but the Irlen Institute seem to be reticent to participate in such research (Clayton, 1990).

Wilkins and Neary (1991) showed that the colour of light that 10 Irlen lens wearers chose to illuminate printed text did not bear a strong relationship to the spectral properties of their Irlen tints. This experimental evidence further detracts from the claims of unique specificity for Irlen tints.

4.2.4.5 Lighting

The protagonists of the Irlen treatment have not usually described, or attached any importance to, the lighting conditions under which they test for tinted lens preference. The various light sources that are used in normal room and office lighting have different spectral power distributions (emit different proportions of various wavelengths of light), and therefore the effect of tints will change under different lighting conditions (McLaren, 1983). This weakens arguments concerning the highly specific nature of Irlen tints.

4.2.4.6 The Idiosyncratic Nature of The Choice of Tint

Yap (1984) investigated the effect of a yellow filter on the contrast sensitivity of normal subjects. All the subjects showed an improvement under photopic conditions, although there was a variation in the degree. Zigman (1990) found that a short wavelength light-absorbing filter enhanced vision in elderly subjects. Wilkins and Neary (1991) showed that many of the tints chosen by Irlen clients maximally absorbed yellow wavelengths and transmitted short wavelengths: others had the opposite effect. Wright (1991) stressed the need for a highly idiosyncratic tint, but noted that sometimes Irlen lens users required a different coloured tint for each eye. She also stated that of the 40% of her Irlen lens wearers who returned for follow-up, 6% were found to require a change of tint. These statements raise further questions concerning the claimed need for a highly idiosyncratic tint.

4.2.4.7 Lack of Published Evidence

A leaflet produced the Irlen Institute (UK) (1989) stated:

> "Any important new discovery must be subject to independent research and exhaustive testing before being accepted as a valid improvement and benefit."

Helen Irlen is a qualified psychologist and her advocates include other psychologists, at least one optometrist, and medically qualified personnel. Although these professionals must be familiar with the need for, and pre-requisites of, rigorous scientific research, such work seems to be noticeably lacking. Several researchers (Stein, 1988; Watkins, 1991), including the author, have submitted research proposals to the Irlen Institute that have not been taken up. Inevitably, this detracts from the strength of their arguments.

4.2.5 Previous Reviews

Many of the references that are cited by workers in this field are difficult or impossible to obtain. Other reviews, therefore, that were privy to this information will now be described.

Rosner and Rosner (1987b were unable to identify any papers that were published in refereed journals and therefore reviewed five unpublished reports, including one by Murphy. They noted that few details had been published on the IDPS, which was used to diagnose SSS. They pointed out the strong suggestion of a placebo effect in Murphy's statement that:

> "individuals who are aided with the Irlen lenses find emotional problems abate. It is not uncommon to see such a change based only on the knowledge that the lenses will be coming".

They described Murphy's screening test for the tinted lenses and his claims that they improve stereopsis, both of which lacked details, full data, or statistical analysis. They pointed out that his technique of relying on parents to telephone negative results was a rather unusual way of defining success from a treatment. Rosner and Rosner (1987b) described syntonics (coloured light therapy) which had been used by some USA optometrists to help the learning disabled, and noted that research in this area was also inadequate. They concluded that there was no reason to condemn or recommend the Irlen treatment.

Stanley (1987) thought that, even in the general population, the degree of individual differences in perception among the colour normal may have been overlooked. He stressed that research in which the colour vision of dyslexic children was tested should not involve colour naming. He briefly reviewed syntonic therapy and concluded that this lacked compelling evidence. Descriptions of the signs and symptoms of SSS also were said to lack appropriate evidence. He briefly reviewed the research of his own group that had found a high correlation between oculomotor problems and the symptoms of SSS. He had also found that some children showed an immediate and others a delayed improvement in reading with overlays, and stressed that this therapy should be viewed as experimental and not proven.

O'Connor and Sofo (1988) in a rejoinder to Stanley (1987), refuted his claim of a lack of "conventional research". They cited 2 published and several unpublished studies, 2 of which have not already been described. The first of these was by Ament, Cariera, and Salmnd in 1983 and found positive reactions to Irlen lenses by 20 wearers, and their teachers and parents. The second study, by Pascoe in 1986, was not described. O'Connor and Sofo (1988) argued that the Irlen therapy was not unreasonably expensive and that Irlen's "major breakthrough" may be linked, in some cases, to central nervous system damage.

Howell and Stanley (1988) noted that light therapy for optometric problems was pioneered by Henning in the 1920s and 1930s. This was partly based on the influence of different wavelengths on the accommodative mechanism, but also on a presumed effect on the autonomic nervous system. This therapy, which was initially termed "chrome-orthoptics" and later "syntonics", had been used to treat: myopia, strabismus, amblyopia, headaches, visual fatigue, reading problems, and general binocular dysfunctions. They reviewed recent research on this therapy (*see* Section 4.3) and described several studies investigating the Irlen lenses. One of these was an unpublished study by Chelva et al. in 1986 that, although lacking a control group, concluded that Irlen lenses increased slow pursuit ability and reading speed. Howell and Stanley (1988) stressed that the contribution from raised expectations and placebo factors needed to be resolved. They concluded that the visual symptoms that this therapy was based upon could be described as abnormal glare sensitivity and oculomotor defects. Some causes of glare sensitivity were outlined and it was suggested that oculomotor defects should be managed by conventional optometric care.

Reeves (1988) highlighted the importance of careful experimental design. He discussed the hypothesis to be tested in research on the Irlen treatment and gave some useful suggestions for future research.

Wilsher and Taylor (1988) pointed out that there was no fast, effective treatment for dyslexia, and that parents' desperation created a climate where bizarre treatments could flourish. They described 3 studies showing that dyslexic children were able to process non-verbal visual material and pointed out that many dyslexic people entered vocations that required prowess at dealing with black lines on white backgrounds (e.g., architects and artists). This argument does not exclude the possibility of a sub-group of dyslexics who have visual problems. The psychological effects of tints were said to include the following: glamour, an excuse for a learning disability, a method of attracting more attention, a novelty, and a placebo. They concluded that proper research studies were needed with a placebo treatment, controls, random assignment to groups, blind assessment of reading, and independent replication. They felt unable to exclude the possibility that the tints did have a genuine positive effect but pointed out that an idiosyncratic improvement should not be generalised to all learning disabled children.

Rosner and Rosner (1988) described the Irlen therapy as "yet another in a long line of purported, but not adequately documented, 'cures' for dyslexia". They thought that learning difficulties were more likely to represent educational problems and that a child's basic resources of time and emotional and physical energy should not be wasted on useless treatments.

Irlen and Lass (1989) advocated a multi-disciplinary approach to the RD and felt that the media had falsely given the impression that tinted lenses were a panacea for reading problems. They stated that 50% of dyslexic people suffered from SSS, which (as usual) was described on the basis of symptoms. These reviewers briefly mentioned 2 papers (Stein and Fowler, 1985; and Lovegrove et al., 1986a) from the countless other studies investigating visual aspects of learning difficulties. These were used to demonstrate that other workers had found that their subjects experienced distortions and movement of print; an alternative explanation might be that this simply illustrates the wide range of causes of blurred vision and diplopia. Irlen and Lass (1989) discussed the diagnosis of SSS, pointing out that all their clients were first seen by an optometrist or ophthalmologist. They mentioned "screening instruments", which were not described, and a broad range of coloured filters were said to be essential. It was stated that the tints resulted in an immediate and permanent improvement but that, owing to the many causes of dyslexia, the children still needed remediation. They suggested some practical methods of minimising the distortions that were intensified by light and colour contrast. These included reducing the illumination and flickering from fluorescent lights and using coloured paper.

Fitzgerald's (1989) review included 2 unpublished papers that the present author has been unable to obtain. A study by Robinson and Conway in 1988 assessed the effect of wearing tinted lenses for 12 months on 44 dyslexic subjects, aged 9 to 14 years. There was an improvement in reading accuracy and comprehension, particularly during the first 6 months, and it was thought that the tints achieved this through improving clarity by reducing contrast. It was pointed out that, contrary to Irlen's claim, this improvement occurred with tints other than the optimal one. Research by Cheetham and Ovenden, in 1987, had assessed 225 dyslexic students who responded to treatment with tinted lenses and reported that these made print more stable, although the authors felt that tints did not cure the reading problem. Fitzgerald (1989) argued that tinted lenses did not improve the clarity of vision, and noted that the claim that the lenses filtered out certain wavelengths was, in a literal sense, incorrect. She concluded that there was no substantiated evidence that tinted lenses helped or that there was a visual problem in dyslexia, although this latter subject was not reviewed. She drew attention to the placebo effect: "It may be suggested that the problem has been taken from within and put on the nose."

Lea and Hailey (1990) noted that tinted lenses could help learning disabled children by a "motivational causation" whereby concerned persons grasped this new remedy and committed themselves to an additional effort, leading to improved reading. They implied that this could not adequately explain the benefits that have been claimed for the Irlen treatment, since such motivational effects would also be observed with other treatment interventions. Other sections of their review, however, cited examples of various treatments that seemed to fulfil these criteria (e.g., vestibular dysfunction, orthomolecular medicine, chiropractic cure, and Doman-Delacato therapy).

Lea and Hailey (1990) pointed out that validation of the Irlen therapy was hampered by the lack of details on the specification of Irlen lenses and the IDPS. They stated that, whilst there were many anecdotal reports of benefit from the use of tinted lenses, there was still a lack of controlled trials to establish their efficacy. They also noted that the mechanism by which this approach may work was unknown. Despite these observations, they went on to estimate the savings to society from this therapy; these calculations were based on the assumption of a proven benefit from tinted lenses. Lea and Hailey (1990) concluded that the studies to date did not establish the place of Irlen lenses in the treatment of the RD.

Solan and Richman (1990) reviewed an unpublished and undated paper by Irlen that attributed SSS to random variations in the discharge rate of retinal receptors, caused by idiosyncratic excessive sensitivity to particular wavelengths of light. Neither this, nor the claim that the tinted lenses were designed to reduce "the random variation in the responses of the photoreceptors" were supported by any evidence. These reviewers next considered SSS and the IDPS, noting that the latter was not available for general distribution and was not listed in "The Mental Measurements Year Book". They identified weaknesses of most research in this area and noted the dichotomy between the commercial interests who seemed satisfied with anecdotal proof and the less disputable evidence required by the professional and scientific community. They concluded that the Irlen therapy lacked a theoretical basis and consistent evidence of an improvement in reading and may be explained by binocular or accommodative dysfunction and/or motivational or placebo effects. They felt that the efficacy of Irlen lenses was, at best, still experimental and public welfare could be compromised if appropriate vision therapy was delayed.

Helveston (1990) noted that in the USA the tinted lens therapy cost $300-500, and that coloured overlays to treat reading disorders were being marketed indiscriminately in supermarkets by individuals who were not affiliated with the Irlen Institute. He suggested that this therapy should still be considered as an experimental procedure. Miles and Miles (1990) concluded, from a brief review, that further evidence was required before the significance of the Irlen therapy could be established. Taylor (1990) reviewed the study by Gole et al. (1989), which was described above.

Podell (1990) reviewed the procedure used by the Irlen Institute (USA). He described the training (over 2 days) of the Irlen screeners who administered the IDPS to new clients. The IDPS included an in-depth history and some visual and perceptual tasks. The clients then viewed text through 6 different overlays (individually and in combination) and their colour preference was recorded. The results of all the screening tests were used to classify how "scotopic" the client was. The client was given the appropriate overlay(s) to use when reading for several weeks and if they proved beneficial he was referred to the nearest Irlen Institute for tinted lens selection. Podell (1990) pointed out that the same highly subjective IDPS was administered to adults and children and advocated caution in giving advice on this therapy.

Solan (1990) concluded that when investigations using tinted lenses and overlays were carefully designed and controlled, the results did not lend support to Irlen's hypothesis. He pointed out that SSS was multifactorial and that it remained to be seen whether its cause was associated with excessive sensitivity of the retina to particular wavelengths of light. He noted that several studies supported the contention that SSS was a manifestation of traditional optometric or ophthalmological problems.

Irlen (1990, unpublished) estimated that the her therapy could help

> "approximately 375,000 of the total school age population in the UK - saving children from school drop out, juvenile delinquency, unemployment and in the worst cases prison."

She asserted that there was "conventional" research evidence of the success of her treatment and gave many anecdotal testimonies by organisations and individuals. She criticised "opticians" who prescribed tinted lenses for the learning disabled for using "a trial by error approach without knowledge of what they are treating." No details were given on the aetiology of SSS.

4.2.6 Conclusion

Most research that has set out to investigate the Irlen therapy has been fraught with methodological weaknesses. Irlen lenses *appear* to help disabled readers and this can, at least in part, be attributed to a placebo effect. Bright colours can subjectively appear to enhance contrast (Scott et al., 1991); this is the principle behind the use of highlighter pens for text. Brightly coloured tinted lenses, therefore, could be described as a self-reinforcing placebo, since they may appear to enhance the contrast of text. Whether any other factors account for the "Irlen lens effect" is unclear, although there is some evidence suggesting that binocular vision anomalies are unusually common in Irlen lens wearers.

4.3 SYNTONICS

Syntonics is a form of coloured light therapy that has been used in the USA to treat a wide range of conditions including myopia, strabismus, amblyopia, headaches, visual fatigue, *reading problems*, and general binocular dysfunction (Kaplan, 1983).

Wurtman (1975) described the direct and indirect effects of light on the human body. One of the indirect effects in rats was that retinal (probably rod) stimulation controlled, through the sympathetic nervous system, some secretory activities of the pineal gland. One such secretion was melatonin, and the author described the effects of increased melatonin in man, which included: inducing sleep; modifying the EEG; and raising the levels of serotonin, a neurotransmitter, and certain hormones.

Kaplan (1983) investigated 2 hypotheses: that RD children had reduced form visual fields and that syntonic stimulation improved these visual fields. He studied 3 groups of children: 10 experimental subjects, who were poor readers; 4 "white light" controls, who were poor readers with binocular dysfunction; and 10 controls, who were good readers with binocular vision dysfunction. The diagnosis of RD was vague, the groups were not matched for sex or intelligence, and it seemed that the experimental subjects may have been selected as having smaller visual fields than the white-light controls. The visual fields were measured before, after, and during treatment, with a monocular campimeter using a 1 mm target of the following colours: white, red, blue, and green. The syntonic therapy involved regular sessions when the subjects looked into a light box at filtered or unfiltered white light. The filters for the experimental group were selected on the basis of refractive error, pupil size, visual field, blind-spot size, symptoms, and history. No more details of these, or of any luminance matching for the different filters, were given. The experimental and white light groups underwent sessions of syntonic therapy when they viewed coloured and white light respectively for fixed periods in the light box. The third group underwent traditional vision training for their binocular vision problems.

The fields of the subjects with a RD were smaller initially than those of normal readers. After treatment, the fields of the experimental group had increased significantly, those of the white light controls had decreased significantly, and those of the binocular dysfunction group had not changed significantly. These results may have been confounded by a differential learning effect for 2 reasons. Firstly, the visual fields of the binocular dysfunction group were measured less frequently than those of the other 2 groups. Secondly, if the experimental group were selected from the white-light controls simply because the former had smaller fields initially, then the experimental group may not have properly understood the instructions on the first visual field test. This is quite feasible since this study did not control for intelligence and some RD children have been shown to have poor selective attention (Hallahan et al., 1978). Kaplan (1983) explained the significant decrease in visual field size for the white-light group by suggesting that the bias of his light source towards the red end of the spectrum would have caused excessive activity of the sympathetic nervous system. This explanation was largely unsupported. He concluded that vision therapy could be enhanced by syntonics, because "it would appear that working with the peripheral subsystems like accommodation and convergence is not as powerful as channelling appropriate colored light directly thru the eyes".

Liberman (1986) summarised the theoretical basis of syntonics. About 10% of the neurons from the retina branch off from the optic nerve before the lateral geniculate nucleus and project to the midbrain (Warwick, 1976); this is the inferior accessory optic tract. Liberman (1986) pointed out that some of these neurons pass through the colour sensitive transpeduncular nucleus in the midbrain to the superior cervical ganglion, which then influences the pineal gland. He described this as the "energetic pathway of the optic system" (c.f., the visual pathway to the cortex) and believed that, through the pineal gland, light had a direct influence on the metabolism and endocrine system. This effect was thought to be wavelength dependant. The author said that diagnostic information for syntonics came from the case history, symptoms, observations, pupillary response, ocular-motor skills, analytical examination, visual field plotting (but only kinetic perimetry was said to be useful), and general clinical experience. His review of the literature in this area does not include any unfavourable papers.

He studied 36 subjects (aged 5-29 years) who were said to be academic underachievers; he did not give any selection criteria or results of academic or psychometric tests. Half the subjects were placed in the experimental group, which was matched for age and sex with the control group. The following tests were administered to all subjects before and after treatment: central form visual fields (monocular stereocampimeter with 1.0 mm white target); visual attention span for objects; auditory attention span for unrelated words; memory for design-power of recall; and the Pierce saccade test (this measures the speed at which the subject can read out randomly spaced digits). The experimental group underwent 20 syntonic treatments, each lasting 20 minutes: the control group did not receive any treatment. The learning disabled children were assumed to have an imbalance in the autonomic nervous system. A sympathetic predominance was said to usually manifest as exophoria and parasympathetic as esophoria; no justification for this assumption was given. The former group received a parasympathetic stimulant (blue) and the latter a sympathetic stimulant (red); the choice of colours was not explained. It was assumed, again without explanation, that subjects with reduced fields but without a significant heterophoria would have their visual fields normalised by yellow-green light.

The author found that the post-treatment increase in visual fields and visual attention span was significantly greater in the experimental group. The Pierce saccadic test was said to suffer from design weaknesses. This study suffered from several weaknesses: the improvement in visual fields was not related to any change in academic achievement; a blind protocol was not used; the controls did not receive a placebo treatment; and the possible confounding variable of intelligence was not considered.

4.3.1 Conclusions

Although syntonics involves coloured light therapy, the background theory and practical details are quite different to the Irlen lens treatment. The limited research that has investigated this therapy is, unfortunately, of similar quality to most of that relating to the Irlen treatment. There is no convincing theoretical or experimental evidence for the efficacy of syntonics.

4.4 POTENTIAL THEORETICAL EXPLANATIONS

4.4.1 Introduction

It was noted in Section 1.5 that dyslexia is likely to have a heterogeneous aetiology. The dearth of valid research leaves us equally unable to dismiss or accept Irlen's claims. Indeed, if her theories were based on scientific fact, the large volume of anecdotal evidence for the success of these tints might be seen as confirmation, rather than as descriptions of a placebo. It is possible that her adoption of meaningless titles, illogical explanations, lack of proper scientific investigation, and commercial approach has caused a potentially important discovery to be dismissed by most as charlatanism. This therapy has suffered from the lack of a valid theoretical explanations and this will now be addressed.

4.4.2 Pattern Glare

4.4.2.1 Epileptogenicity of Patterns

Approximately 5% of patients referred for an EEG to investigate known or suspected epilepsy will develop a photo-convulsive response to intermittent photic stimulation (IPS) (Jeavons and Harding, 1975). Bickford et al. (1953) reported that patterns of stripes can also provoke seizures. Jeavons et al. (1972) found that the likelihood of paroxysmal EEG activity (indicating an epileptogenic stimulus) in photosensitive epileptics was increased if the IPS was patterned.

Wilkins and Lindsay (1985) reviewed the physiological mechanisms of common forms of reflex epilepsy, including epilepsy associated with reading. They noted that the incidence of paroxysmal activity was significantly reduced when patients with reading epilepsy used a mask that allowed only 3 lines of text to be seen clearly at one time. They described a case history with reading epilepsy who suffered from allergies, headaches, "poor binocular co-ordination" and had a family history of migraine.

Wilkins et al. (1979) thoroughly investigated people with pattern sensitive epilepsy. They showed that the gratings that were most likely to induce paroxysmal activity had a spatial frequency of 1-4 cycles/° and were of contrast greater than 0.3. Alternate isoluminant red and green gratings did not elicit a response and the chance of induced activity increased with the size of the target pattern. Mixed gratings and checkerboards were also less likely to induce paroxysmal activity, suggesting that the trigger for paroxysmal activity lay in orientation sensitive cells, and hence not in the lateral geniculate nucleus. Investigations using binocular rivalry and counterphase interocular flicker suggested that the trigger involved binocular interaction. The authors concluded that the locus for the trigger mechanism was cortical and that paroxysmal activity arose when neural activity reached a threshold level; possibly because of cortical hyperexcitability owing to a deficient inhibitory mechanism. They noted that their research had not differentiated spatial from temporal factors; for example, microsaccades could cause intermittent temporal stimulation of retinal cells by patterns.

Darby et al. (1980) investigated the characteristics of patterns which were most likely to produce seizures (Table 4.1). They found that 64% of patients who were sensitive to IPS were also sensitive to certain stationary or oscillating patterns. This corresponded to approximately 3% of all people with epilepsy. They advised such patients to wear dark glasses or to cover one eye when they were unavoidably exposed to critical patterns.

characteristic	factor increasing epileptogenicity
pattern type	parallel equal-sized black and white stripes
spatial frequency	2 c/°, range from 1-4 c/°
visual angle	larger, rarely sensitive if less than 16°
contrast	high contrast, black on white, greater than 30%
brightness	above 200 cdm^{-2}
pattern movement	oscillation orthogonal to stripes, optimum at 20 Hz
binocular vision	binocular

Table 4.1 The characteristics that were found by Darby et al. (1980) to make patterns most epileptogenic.

4.4.2.2 Patterns, Migraine, and Visual Discomfort

Wilkins et al. (1984) investigated the effect of patterns on epilepsy, migraine, headache, and visual discomfort. They concluded that certain patterns of stripes (*see* Figure 4.1) were unpleasant to look at and may induce illusions of colour, shape, and motion. These illusions were reported more frequently by people who suffered frequent headaches; a lateralisation of pain correlated with a lateralisation of illusions. The optimal characteristics of the patterns that produced illusions closely resembled those that elicited epileptiform EEG abnormalities in patients with photosensitive epilepsy (Table 4.1).

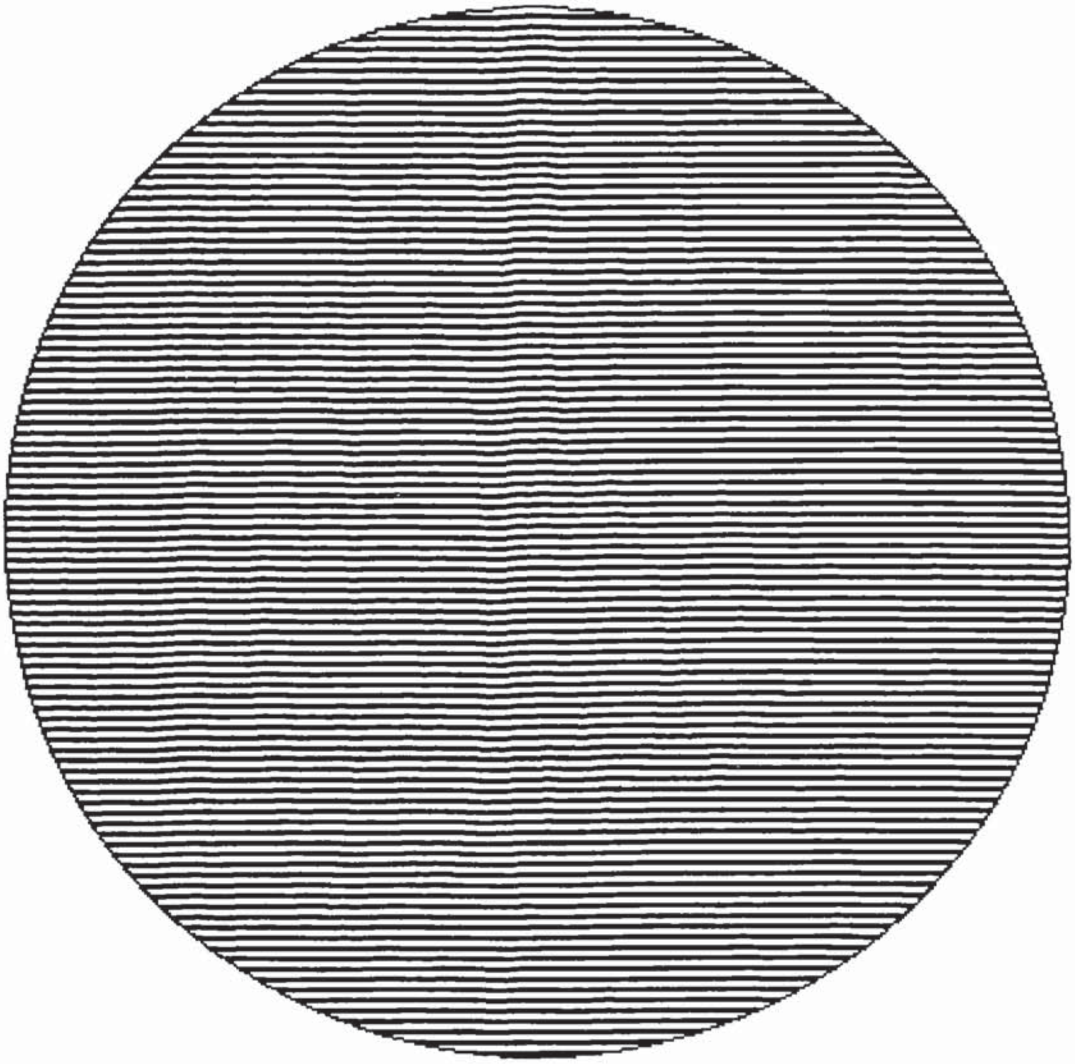

Figure 4.1 A pattern whose characteristics, when viewed at 25 cm, may cause pattern glare...

Meldrum and Wilkins (1984) suggested that photosensitive epileptiform anomalies may result from a minimal diffuse failure of cortical inhibition. Wilkins et al. (1984) hypothesised that sensory stimulation by certain patterns of stripes may cause a similar breakdown of inhibitory mechanisms. They suggested that if the discharge remained localised within the visual cortex then neurons may be inappropriately excited, producing anomalous visual effects. They proposed, therefore, a condition of cerebral hyper-excitability, with a scale of severity ranging from epilepsy, through migraine, to discomfort. A causal relationship was suggested by the similarity of the visual precipitants and by literature suggesting that 40% of people with photosensitive epilepsy reported various forms of ocular discomfort (headache, sore eyes, etc.) that were induced by potentially epileptogenic stimuli.

Marcus and Soso (1989) investigated pattern sensitivity in 102 randomly selected adults and 17 neurology clinic patients whose primary complaint was headache. Pattern sensitivity occurred in 82% of 38 migraineurs, 18% of the 22 subjects who suffered from non-migraine repetitive headaches, and none of the 42 subjects who experienced no headaches. This interesting study suffered from a few procedural weaknesses: the subject numbers did not sum to the total population under investigation, the definition of "recurrent headache" was vague, and the diagnosis of pattern sensitivity required the subjective judgement of the examiner.

4.4.2.3 Pattern Glare and Reading

Wilkins and Nimmo-Smith (1984) argued that printed text made up a pattern of stripes that may provoke some of the eye-strain and headaches that were attributed to reading; they called this pattern glare. One third of their volunteers, who were predisposed to asthenopia when reading, derived substantial benefit from an aid that covered most of the page, leaving three lines exposed. Reference was also made to an article, as yet unpublished, by Findlay and Wilkins who found that patterns of stripes increased the standard deviation of the position of the eye, and that people with unstable fixation tended to see more illusions. They suggested that the reading aid, by attenuating the pattern of stripes, enabled people with relatively poor oculomotor control to find words more readily.

Wilkins and Nimmo-Smith (1987) measured the spatial properties of printed text and showed that it did resemble a pattern that might elicit an epileptiform response or pattern glare. They found that subjects' judgements of clarity were influenced by the spatial properties of the text, particularly the spacing between the lines.

Evans et al. (1991) investigated the role of pattern glare in a simulated reading task using a paradigm that controlled for a placebo effect. One hundred and fifty-one undergraduate students were questioned about a history of headache, migraine, and epilepsy; and any anomalous visual effects that they saw whilst viewing a grating that was designed to cause pattern glare. These problems were not related to the number or type of anomalous visual effects ($p > 0.10$). Five of these subjects who had experienced most pattern glare ("experimental group") and 6 who had experienced least pattern glare ("control group") chose overlays of a colour that made the pattern "most comfortable to look at"; the colour that was chosen was idiosyncratic. These groups then carried out two timed simulated reading visual search tasks, one that had a "crowded" layout so as to induce pattern glare, and one that should not have caused pattern glare ("uncrowded"). The effect of the overlays at improving performance on the crowded task relative to the uncrowded one was greater in the experimental group ($p = 0.057$). It should be stressed that this study investigated a group of adults who were unlikely to have a reading disability. The results suggested that people who experienced pattern glare performed better with tinted lenses at a closely spaced simulated reading search task than subjects who did not experience pattern glare. It would be interesting to repeat this study with RD children; the paradigm would allow a double blind placebo controlled investigation of pattern glare and tinted lenses in dyslexia.

4.4.2.4 Is SSS a Manifestation of Pattern Glare ?

Symptoms.

The symptoms that have been associated with SSS will be described first; they will be numbered in superscript for subsequent matching with the symptoms of pattern glare. Stanley (undated) listed the following areas of difficulty for sufferers of SSS:

> 1. Photophobia[1], inability of a person to tolerate bright light and glare[2]. Problems with black on white[3]. Shapes became distorted[4].
> 2. Visual resolution, the difficulty of keeping an image constant[5]. The page was distorted with letters moving[6], blurring[7], getting darker and lighter[8], seeing double images[9], words spreading[10], flashing[11] and flickering[12] on the page. The whole page appeared to swirl or "white out" altogether[13].
> 3. Sustained focus. Most sufferers had trouble keeping the words in focus[14], and this was said to be independent of refractive correction. She included in this category people whose focus was clear but who found that after a short time reading they were tired[15], their eyes watered[16], hurt[17], burned or itched[18], and had to take a break[19].
> 4. Span of focus. Here, the Irlen workers appeared to be referring to the number of letters comprehended during a fixation pause (normally referred to as the average span of recognition). This was much reduced[20], punctuation was not observed, and comprehension was only obtained by re-reading.
> 5. Depth Perception. This was stated to be poor[21], not just when reading.
> 6. Eye Strain[22]. This reduced the reading time, causes blinking, staring, and squinting and poor concentration.

The symptoms that have been associated with pattern glare will now be described; when these correpond with those described above they will be identified by the appropriate superscripted numbers. Wilkins et al. (1984) described the following visual effects of viewing patterns, in descending order of frequency:

"colours (red, green, yellow, blue), diamond-shaped lattice, shimmer[12], blurring[14], dazzle[1], glare[2], bending of the lines[4], fading[8], 'blobs'[4], and flickering[12]. To our surprise, 11 out of 29 volunteers also listed adverse effects such as 'eyeache'[22], tiredness[15], headache or 'dizziness'."

In the same series of experiments Wilkins et al. found that in unilateral headache patients "temporary blurring of vision"[7] was associated with the total number of illusions reported ($p < 0.02$). Wilkins and Nimmo-Smith (1984), in their study relating patterned glare to discomfort when reading, found the following eight symptoms of eyestrain were most common:

irritation[17] or soreness[18] of the eyes, pain in response to light[1], faint colours surrounding objects, spots or shapes in front of the eyes[4], narrowing of vision (one or both sides)[5], redness of the eyes[22], temporary blurring of vision (despite glasses if worn)[14], dryness of the eyes[18]. Furthermore, there was a significant difference between the subjects who planned to continue using the aid, which reduced patterned glare, and those who did not, in terms of the mean reported incidence of the eight symptoms.

Sex Ratios

Critchley's (1964) review concluded that approximately 75% of dyslexic people were males. Hess et al. (1974) noted from the literature that about 36% of people with photosensitive epilepsy were male, although migraine is more common in females than males (Berkow, 1982; Marcus and Soso, 1989). The literature on the relative incidence of dyslexia, migraine, and epilepsy in the sexes does not suggest, therefore, a common aetiology. However, all these conditions are thought to have a heterogeneous aetiology.

Dyslexia and Headaches

Holland (1986) reported on the children seen in an optometric practice over a six month period, excluding those referred for investigation of RD. Sixty per cent of those who were found to have a RD presented with a headache compared with only 27% of the total sample.

Stanley (undated) stated that headaches were a common symptom of SSS. Yeung and Heeney (1986) cited Dr. Murphy, a Hong Kong psychologist practising the Irlen techniques, as suggesting "disruptions in the brain by abnormal perception of colour might give a dyslexic splitting headaches and eye strain."

Dyslexia and Epilepsy

Goldberg et al. (1960) presented evidence, from EEG's and psychometric tests, suggesting that some dyslexic people suffered from subclinical brain damage. The EEG abnormalities were said to be similar to those in focal epilepsy.

Prechtl (1962) suggested that many children with reading difficulties suffered from minimal brain damage and investigated 50 children who demonstrated choreiform movements. Reading problems were present in 90% of these cases, all of whom exhibited choreiform eye movements. They found that 12% had frequent epileptic attacks, and concluded that a distinct neurological syndrome existed that suggested the presence of minimal brain damage. Newton (1985, unpublished correspondence) suggested a link between SSS and photo-sensitive epilepsy.

Critchley (1964) suggested that there may be a subgroup of dyslexic individuals who had minimal brain damage resulting from trauma at birth. He believed that descending degrees of trauma could lead to stillbirth, neo-natal death, cerebral palsy, epilepsy, behavioural disorders, and dyslexia; although he stressed that these were not "genuine developmental dyslexics". Critchley and Critchley (1978) defined this subgroup as secondary dyslexia (*see* Section 1.5.3.1).

Hulme (1981, p. 14) described a study in which 18% of epileptic children and 40% of children with cerebral palsy and "other brain conditions" were retarded in reading. Hughes (1982) described EEG abnormalities in dyslexia, but it was unclear whether their presence is related to a cause or effect of the reading disability (Benton, 1975). An anecdotal report by Duane (1991) described abnormal EEG findings and an increased incidence of nocturnal seizures or febrile fits in dyslexia.

Instability of Fixation

Wilkins and Nimmo-Smith (1984) described unpublished research by Findlay and Wilkins which showed that:

> "patterns of stripes surrounding a fixation target can increase the SD of the position of the eye. The SD varies considerably from one person to another, and people with unstable fixation tend to see more illusions."

It was shown in Section 2.5 that abnormal eye movements may be a correlate of dyslexia. Few studies have assessed fixation stability in dyslexia, although Raymond et al. (1988) did find fixation instability to be a correlate of dyslexia. This was attributed, however, to cerebellar dysfunction.

Treatment.

Wilkins et al. (1975) reported a case where pattern sensitive epilepsy was successfully treated by monocular occlusion. This was probably linked to binocular interaction in pattern sensitive epilepsy (Wilkins et al., 1979; Darby et al., 1980). Stein and Fowler (1982, 1985) found that up to two thirds of dyslexic children benefited from occlusion (*see* Section 3.3).

The aids used by Wilkins and Nimmo-Smith (1984) to reduce asthenopia when reading were found to be equally effective if made of a translucent material, which simply reduced contrast. The treatment suggested by Darby et al. (1980) for pattern sensitive epilepsy was to wear dark glasses or cover one eye. The observation by Wilkins and Nimmo-Smith (1984) that a symptom of pattern glare was "seeing colours" needs further investigation.

Colour Specificity

Hess et al. (1974) noted that tinted spectacles could help in photosensitive epilepsy. They stressed, however, that they would be ineffective if prescribed indiscriminately owing to individual differences in the colour of tint required. Jeavons and Harding (1975) reviewed the literature on colour as a photic stimulation factor for epilepsy. This was equivocal, but suggested that tinted spectacles may result in a clinical relief of seizures if the tint is chosen on the basis of the patient's response to photic stimulation with coloured lights. They investigated the sensitivity to epileptiform EEG anomalies of 16 photosensitive patients with IPS by different coloured stimuli. Many patients showed only slight differences in sensitive ranges between the different colours and the results were largely idiosyncratic, although the group as a whole showed a slightly reduced sensitivity to red stimulation.

Wilkins et al. (1975) discussed a case study whose pattern sensitive epilepsy seemed to be triggered in complex cells of the striate cortex. They pointed out that few cortical cells were colour specific: the majority were only sensitive to brightness changes. Wilkins (1990) suggested that some children with learning difficulties may be manifesting localised hyper-excitability of "patches" of cells in the striate cortex. He suggested that if the complex cells in the localised area were predominantly receptive to light of a certain colour this could result in a sensitivity to light of specific wavelengths. This theory could allow for pattern sensitive individuals receiving relief from highly specific and idiosyncratic tints.

An Anatomical Model

The subtle cortical abnormalities that have been found in some dyslexic individuals (*see* Section 1.5.3.1) may provide an anatomical model for Wilkins' theory. Galaburda and Kemper (1978) described an autopsy of a person who had suffered from dyslexia. They found an unusually wide left cerebral hemisphere, an area of polymicrogyria in the left speech region, and mild cortical dysplasias in several areas. One of these areas was the occipital cortex, which showed disordered layering, scattered coarse cells, and subcortical neurons. This patient also had a history of well-controlled epilepsy, and similar cortical abnormalities have been found in cases of epilepsy (Taylor et al., 1971). Indeed, the hypothesised anatomical link between pattern sensitivity in epilepsy and dyslexia might be expected to result in a strong individual and familial link between dyslexia and epilepsy. Only a relatively small number of authors have noted such a link (*see* Section 4.4.2.4).

This theory could be investigated experimentally by making use of the fact that these cerebro-cortical abnormalities in dyslexia have been virtually confined to the left hemisphere. If dyslexic subjects who were prone to pattern glare were shown 2 stimuli comprising vertically divided hemifields, the number of anomalous visual effects should be greater when the pattern is in the right visual half field. If these subjects were selected from Irlen lens users, then the effect of tints on the anomalous visual effects could be investigated. For both experiments, the target where the grating was on the left side of the fixation point (and hence imaged in the right hemisphere) could act as a control.

4.4.3 Fluorescent Lighting

Wilkins (1986) analysed the saccadic eye movements when normal adult subjects viewed text that was presented on a visual display unit (VDU) or on paper that was illuminated by a fluorescent light. The VDU screen replenishment rate was 50 or 100 Hz and the fluorescent tube flickered at the normal 100 Hz or at a very high frequency, which was effectively continuous. The subjects made more and larger saccades, suggesting decreased accuracy, for the low frequency conditions, and most preferred the 100 Hz display. Neary (1989) investigated the effect of flicker of various frequencies on accommodation in 2 normal adult subjects. The accommodative response for several target vergences (0.5 to 3.5 D) was significantly increased by flickering at 25 and 50 Hz, but was not impaired by flickering at higher frequencies.

Wilkins and Neary (1991) noted that the flickering from conventional fluorescent lamps had been shown to influence the firing of neurons in subcortical visual structures and may affect accommodation and ocular motor control. They pointed out that the majority of pulsating light from a fluorescent tube had a wavelength less than 550 nm and, therefore, would be selectively reduced by most of the Irlen tints that their subjects had selected. They suggested that these subjects may be unusually susceptible to the effects of light pulsation because of a family history of migraine and/or a defect of the transient visual system (*see* Section 4.4.4).

Wilkins and Wilkinson (1991) described a tint that was designed to minimise the luminous pulsation of light from fluorescent lamps. A compromise design was necessary to avoid excessive interference with colour perception and for the tint to have a cosmetically acceptable colour appearance. They described some case histories of patients who appeared to benefit from the use of the tint. One of these was a lady with photosensitive epilepsy and they noted that the spectral transmission of the tint was similar to many Irlen lenses.

4.4.4 Transient System Deficit

4.4.4.1 Iconic Persistence

Riding and Pugh (1977) measured reading performance and the image persistence in visual sensory (iconic) memory in 36 children, aged 9-10 years, who were randomly selected from an urban school. They found that children with unusually long or short iconic persistence had significantly worse reading performance than those with moderate iconic persistence. The effect of intelligence on this difficult task was not controlled for.

Høien (1982) compared the iconic persistence of 58 RD children with 54 controls (normal readers) who were matched for age, background, and IQ. There was little variation in iconic persistence within the control group, which was described as "moderate iconic persistence". Only half the RD group demonstrated this moderate persistence, 40% demonstrated unusually long, and 10% unusually short, persistence. These subjects were further investigated using a tachistoscope and pro-active and retro-active interference (a masking technique). The results suggested that unusually short or long iconic persistence could, under some experimental conditions, interfere with the perception of letters. This study lacked a detailed description of the subjects or of the procedure. Fricker (1987-1988) suggested that Høien's (1982) findings may be related to the use of tinted lenses in dyslexia.

Lovegrove et al. (1980b) found that the persistence of iconic memory was different in the RD, and that this difference varied as a function of the spatial frequency of the stimulus; the persistence was longer at lower spatial frequencies. Lovegrove et al. (1986a) combined this with other experimental evidence to suggest that approximately 70% of specific reading retardates had a deficit of the transient visual system (*see* Section 2.7.1).

4.4.4.2 Colour and The Transient System

Gouras (1985) noted that one type of magnocellular retinal ganglion cell was preferentially inhibited by long wavelength stimuli; these have been called Type IV Cells. He suggested that the excitatory discharge to green but not red lights in these cells may result from a maintained rod signal. This raises the faint, but amazing, prospect of SSS being appropriately named. Wilkins (1991a) suggested that the effect of colour on both visual discomfort and epilepsy may be related to the tonic suppression of magnocellular neurones in the lateral geniculate body by diffuse red light. This linked pattern glare with a disorder of the magnocellular system and may relate to the hypothesised transient system deficit in dyslexia. There is, however, some uncertainty over the differential spectral properties of the transient and sustained visual systems (Ingling, 1990).

Solman et al. (1991) measured the contrast sensitivity of normal and disabled readers using each of 4 filters: clear, grey, and those that gave the subject the best and worst performance at a spatial localisation task. It is unclear why this method, which did not seem to relate to reading, was used to choose the tints. The groups both contained 10 children and were selected from a normal population. They were matched for age but not for intelligence, although data on this variable were available. The reading retardation of the RD group appeared to be severe, but was not assessed conventionally. The contrast sensitivity was measured at 6 spatial frequencies from 0.4 to 12.8 cycles/° using Arden plates; one measurement was taken at each spatial frequency under each condition. The RD children's "best" coloured filter significantly reduced their contrast sensitivity as the spatial frequency increased; there was very little change in sensitivity for the good readers using their "best" filters. Three way interactions between group, spatial frequency, and clear v. grey lenses were not significant.

Solman et al. (1991) hypothesised that tinted lenses may manipulate the input to the colour receptors and thus improved transient-on-sustained inhibition in cases of a transient deficit. This theory was supported by their results and the mediation of colour vision by the sustained system. Further support came from Williams et al.'s (1987) findings that diffusing sheets improved RD children's performance at a search task, although neither of these studies included a test of transient function. Indeed, Solman et al.'s (1991) "clear" condition did not find the low spatial frequency contrast sensitivity loss in the RD group that has been used as evidence of a transient deficit by other workers (*see* Section 2.7.1). This study assumed that any transient system deficit played a causal role in RD and did not give any orthoptic test results. The authors stressed that more work was necessary before the efficacy of tinted lenses in dyslexia could be supported.

Williams (1991a) suggested that colour influences the temporal responses of the transient and sustained channels. She used meta-contrast masking by red, white, and blue stimuli to show that transient processing in 5 normal and 5 dyslexic children was fastest for blue and slowest for red wavelengths. The relative rates were similar in both groups, although the data suggested that transient processing was slower under all conditions in the dyslexic group. The dyslexic group's rate of transient processing with the blue mask was similar to that of the control group with a white masking target. The author hypothesised that a blue filter could re-establish the normal rate of transient processing and investigated this with an intervention study. The reading comprehension of 18 RD children and 18 normal readers was measured whilst they read passages that were set at each subject's reading level. The passages were read; in a counterbalanced order, with each of 5 overlays: blue, green, red, grey, and clear; and the results were analysed relative to the clear condition.

All subjects read more accurately with the blue filter, both groups were less accurate with the red filter, and the green filter had little effect in both groups. The grey filter had a minimal effect in the control group but in the dyslexic group it improved the accuracy to a similar degree as the blue filter. The author explained this confusing finding as the grey filter specifically impairing the contrast sensitivity. A more plausible explanation for the RD group's result may be that the grey and blue filters both reduced the strength (contrast) of the sustained image thus improving transient-on-sustained saccadic suppression. This theory does not explain why the red filter, which subjectively appeared to be darkest (Williams, 1991b) did not have a similar effect. It is also difficult to explain why the control group performed better with the blue filter than with a clear filter. Williams (1991b) noted that the results were highly idiosyncratic (this is reminiscent of reports by Irlen, 1983). It may be premature, therefore, to draw conclusions from her work until it is repeated with larger groups. This study was carried out under normal fluorescent lighting, the filters were not matched for density, and an alternative, accommodative, explanation was not investigated.

Buchsbaum and Gottschalk (1983) used information theory to suggest that efficient colour transmission was achieved by a transformation of the 3 cone inputs into an achromatic and 2 opponent chromatic channels. The opponent chromatic channels were R-G and Y-B (which equates to (R+G)-B). They empirically tested the principles of the theory and discussed the relationship with other theories. Wilkins (1991c) used this theory to suggest an alternative hypothesis linking the use of tinted lenses with a transient system deficit in dyslexia. He argued that an imbalance in these channels could be linked to a transient system deficit and may account for the benefit from tinted lenses in dyslexia. This hypothesis requires more theoretical and experimental investigation, particularly to investigate whether such an anomaly could occur without a colour vision defect and how it might account for discomfort from particular wavelengths.

4.4.4.3 Chromatic Aberration

If a person's transient visual system fails to fully inhibit the sustained system after a fixation pause, then one potential therapy is to reduce the contrast of the sustained image, which could be achieved by blurring. Williams et al. (1987) found that the performance of poor readers at a visual search task improved when the stimulus was blurred; this did not influence the performance of good readers.

Wilkins and Neary (1991) found that the majority of Irlen tints chosen by their subjects absorbed maximally at 550 nm whilst showing a relatively high transmission at both extremities of the visible spectrum. This type of tint would increase the effect of ocular chromatic aberration. Campbell and Gubisch (1967) showed that ocular chromatic aberration usually results in a reduction in V/A and contrast sensitivity, and Emsley (1977) gave the maximum chromatic aberration of the eye as about 3.00 D. A tint that enhanced the natural chromatic aberration of the eye would cause blurring and hence reduce the contrast of the image. This might re-establish normal iconic persistence and/or improve transient on sustained suppression in dyslexia.

The effect of some Irlen tints, described by Wilkins and Neary (1991), on chromatic aberration was estimated by the present authors from the product of the spectral sensitivity curve and the transmission curves of the lenses. Further computation to arrive at integrated blur due to chromatic aberration was derived, but it was concluded from graphical inspection that the amount of extra induced chromatic aberration was clearly too small to merit such a detailed comparison. Hence, from the sample of Irlen tints analysed by Wilkins and Neary (1991), this particular hypothesis seems untenable. This conclusion was supported by Stone et al. (1990) who found that longitudinal chromatic aberration did not influence contrast sensitivity.

Williams and LeCluyse (1990) noted that the validity of the transient / sustained distinction in human vision has been questioned. This classification, however, is not essential to the above hypothesis. Høien (1982) suggested that icon length could be regulated using coloured letters and that prolonged persistence would be helped by reducing the contrast of the target. It should be noted that the antithesis of our hypothesis would suggest that his small group of poor readers who demonstrated unusually short iconic persistence may benefit from a tint that enhanced contrast by transmitting maximally at 550 nm. Yap (1984) showed that contrast sensitivity of normal subjects was enhanced by such a filter. Wilkins and Neary (1991) did find a small number of their Irlen lens users had selected this type of tint.

4.4.4.4 Interference Between Images From Successive Fixations

Eye movements result in a repetitive pattern creating an *intermittent stimulation of retinal* cells, which may be similar to that caused by a flashing light. Wilkins et al. (1980) investigated whether this could explain the convulsive response to a pattern in some cases of photosensitive epilepsy. This may be supported by the observation that after-images of patterns failed to elicit paroxysmal activity; although, this may result from insufficient retinal stimulation. Wilkins et al. (1980) found that checkerboards were less epileptogenic than stripes, despite having a relatively larger number of brightness contours. This suggested that pattern sensitivity did not result from eye movements causing an intermittent stimulation of the retina by the pattern's brightness contours.

The possibility, however, that this explanation accounts for anomalous visual effects in dyslexia has not been investigated. If Breitmeyer's (1980) theory of the role of the transient and sustained systems in reading is correct, then a transient system deficit may result in some superimposition of subsequent retinal images. This might not be expected to cause a debilitating degree of visual confusion since the first image would be fading when the second was formed. This hypothesis would, however, predict that the contrast of the striped pattern of lines of print would be increased by the predominantly horizontal direction of reading eye movements. This could increase pattern glare in susceptible individuals. Any vertical or oblique eye movements may cause a Moire pattern, contributing to symptoms of anomalous visual effects.

4.4.5 Binocular Vision Anomalies

A similar argument to that in Section 4.4.4.4 could be applied to interference between the images from the 2 eyes. Unstable binocular vision has been found more often in dyslexia, but it is not clear whether instability occurs during reading eye movements (Evans and Drasdo, 1990). The role of suppression and ocular dominance may be important, but the literature on this is also equivocal (*see* Chapter 3).

Several studies have found an unusually high incidence of binocular vision anomalies in dyslexic children who seemed to benefit from tinted lenses (Irlen, 1985; Scheiman et al., 1990; Grisham et al., 1990; Blaskey et al., 1990; Solan, 1990; Wilkins and Neary, 1991; and Holland et al., 1991). Holland (1987, 1988) suggested that tinted lenses help simply by alleviating photophobia that accompanies unstable binocular vision. He did not, however, link this type of photophobia with the need for highly specific and idiosyncratic tints. It is possible that a transient system deficit could account for binocular dysfunction in dyslexia (Stein, 1991a) and for a benefit from tinted lenses (*see* Section 4.4.4); more research is needed to investigate this possibility.

4.5 CONCLUSIONS

Syntonics is, compared with tinted lenses, a rare treatment for RD and it lacks a firm theoretical or experimental basis. At present there is no conclusive proof (from rigorous scientific studies) that the use of tinted lenses by dyslexic people has a positive influence on reading performance other than that which can be attributed to a placebo effect. There is, however, extensive anecdotal evidence for a benefit from these lenses, and there is diametric opposition between those who believe this therapy to be successful until proven otherwise, and those who believe that the burden of proof should lie with advocates of the treatment.

The positive response of some children to the tints seems to be much greater than one would expect from a placebo, and this may account for the suggestions of a sub-group who derive significant benefit from these lenses (e.g., Gole et al., 1989). It is difficult to quantify an anticipated placebo effect and it remains to be seen whether this sub-group is helped because of a real disability, or are simply more receptive to a placebo. In any case, there is no evidence to suggest that these tints are in any way harmful, or to support the claims that there is anything unique about these lenses that precludes their supply through normal channels. These tints, however, may need to be highly specific (Wilkins, 1991b).

Several potential theoretical explanations for a benefit from this therapy have been discussed. The key factors in these hypotheses are: pattern glare, fluorescent lighting, transient visual system deficit, and binocular vision anomalies. These expand the framework for investigating this therapy. If tinted lenses are shown to have a genuine effect, then the explanation could involve a combination of these factors, possibly in association with as yet undiscovered explanations.

CHAPTER 5
HYPOTHESES

5.1 Summary of Review Chapters & Implications For Research

Section 1.3 highlighted the importance of a careful diagnosis of dyslexia, taking into account the child's intelligence. It was noted in Section 1.8 that ocular pathology may reduce reading speed but does not normally cause the type of reading difficulty that occurs in dyslexia.

It was concluded in Chapter 2 that depressed V/A and hypermetropia may be weak correlates of dyslexia, and that binocular vision and orthoptic problems, particularly vergence dysfunction, seem to be relatively stronger correlates. Additionally, some studies had found defective accommodation to be associated with dyslexia, and a priority of the present research was to further investigate these variables. Some of the controversy in the literature can be attributed to a failure to consider certain confounding factors. Optometric tests that in principle measure the same variable may produce different results (Pickwell, 1984a; Feldman et al., 1989), and subtle variations in test design may have differential effects on good and poor readers (Eames, 1934; Stein et al., 1988). Many studies were also based on the assumption that visual problems played a major causative role in dyslexia and hence quantified results according to clinical criteria as "normal" or "abnormal".

Several studies, using different investigative techniques, have supported the argument that there may be deficit of the transient visual system in dyslexia (*see* Section 2.7.1). This research has typically employed small group sizes, and has not yet applied more than one of the "tests for a transient system deficit" to the same group of children. The present work aimed to do this, and to investigate the possibility of a link between defective visual processing and other optometric factors in dyslexia.

It has still not firmly been established whether abnormal reading eye movements in dyslexia are a cause or effect of the RD (Singleton, 1988). The failure to reach a conclusion on this issue, despite many studies using various paradigms (*see* Section 2.5), suggests that the further repetition of similar procedures would be unlikely to make a significant contribution to the literature. This conclusion was supported by Hartje (1972) who reviewed a number of severe eye movement abnormalities and their effect on reading and concluded: "It seems that eye movement pattern in reading cannot always be considered as a valid indicator of either a normal or a disturbed reading performance". Recent research has attempted, unsuccessfully, to resolve the controversy concerning saccadic eye movements for sequential tasks in dyslexia (Barnard and Thomson, 1991;

Biscaldi and Fischer, 1991; and Fields et al., 1991). Some of the contradictions in the literature may be attributed to differences in the types of saccadic tasks that have been investigated (Biscaldi and Fischer, 1991).

A more profitable role for eye movement analysis would be to investigate whether dyslexic children with a binocular vision problem demonstrated vergence instability during reading, or non-verbal simulated reading tasks. To this end, the author experimented with methods of eye movement monitoring, including: electro-oculography using new electrode designs and EEG averaging techniques; a single Purkinje image device with video-recording facilities and dedicated software; and limbal reflection devices. A prerequisite was that the apparatus should be able to reliably and repeatably detect vergence drifts which may be 5 minutes of arc or less (Mallett, 1988); none of these methods consistently achieved this level of accuracy.

Cornsweet and Crane (1973) described a dual Purkinje image device and Schor and Horner (1989) used this to measure vergence responses to within 0.5 minutes of arc; unfortunately this equipment is prohibitively expensive and does not appear to be in use in the UK (Thomson, 1990). The only other techniques that may approach the desired level of accuracy are "contacting methods", where tightly fitting contact lenses are worn by the subject (Haines, 1980); these were not considered appropriate for research involving unselected children. It was therefore decided that to include eye movement analysis in the present research would not make the best use of available resources.

The literature reviewed in Chapter 3 suggested that most measures of ocular dominance were not related to RD, but that an unstable response on the Dunlop test may occur more often in dyslexia. It was also concluded that future research should attempt to improve the reliability of the Dunlop test, and should control for intelligence. The research reviewed in Chapter 4 concerning tinted lens therapies and dyslexia was inconclusive, mainly owing to a failure to control for the placebo effect. Until recently, this therapy has lacked a satisfactory theoretical explanation, and a priority of the present research was to investigate the hypothesis that pattern glare may be a correlate of dyslexia.

Most researchers who have investigated visual aspects of dyslexia have only studied one particular aspect; for example, those studying ocular dominance have not normally related this to binocular function, and the research on a transient system deficit has never been related to the other optometric correlates. This may have limited our understanding of the role of visual factors in dyslexia, and the present research adopted a more integrative approach.

5.2 Scope and Aims of The Present Research

It was concluded from the literature review that the following key areas should be investigated:

basic refractive tests
binocular vision and orthoptic tests
tests of accommodation
the Dunlop test
pattern glare
investigations of parallel visual processing

The first aim was to investigate these areas as possible optometric correlates of dyslexia, and the second was to assess the relationship between these factors. The third aim was to discover whether any correlates that had been identified were causally related to the reading retardation; this was undertaken in 2 ways. A visual search task was designed that required the same visual skills as reading, but did not require higher level linguistic skills; this was used to test whether a visual factor was likely to have a direct effect on reading performance. It is also possible that these factors could have an indirect influence by causing asthenopia or transient visual symptoms; this was investigated by an analysis of symptomatology.

5.3 Hypotheses

5.3.1 General Hypotheses

The following general hypotheses were investigated in the present research:

1. Hypermetropia is present more often and to a greater degree in the dyslexic sample.
2. Binocular vision dysfunction (particularly reduced vergence amplitudes) is present more often in the dyslexic sample.
3. Accommodative dysfunction is present more often in the dyslexic sample.
4. A fixed reference eye is less well-established in the dyslexic sample.
5. Pattern glare is more prevalent in the dyslexic sample.
6. A defect of the transient visual system is present in the dyslexic sample.
7. There is a link between some of the above hypotheses, particularly between the presence of a defect of the transient visual system and binocular and accommodative dysfunction.
8. Optometric deficits in dyslexia impair performance at a simulated reading task.
9. Optometric deficits in dyslexia are associated with increased symptoms of visual disturbances and asthenopia.

5.3.2 Specific Hypotheses

The experimental work in this thesis was carried out in 2 studies. The pilot study was a small project whose main purpose was to investigate the most appropriate investigative techniques for the main study. Many of these tests were modified for the main study, and several new techniques were developed. Hence, several of the hypotheses that are described in this section will not be encountered by the reader again until Chapter 7.

5.3.2.1 Symptoms and History

Table 5.1 lists the main hypotheses that were specifically investigated by the symptoms and history. The theoretical foundations of these hypotheses can be found in the review chapters (Chapters 4 and 2 for 1-8 and 9 respectively in Table 5.1); these are briefly summarised in Table 5.1.

	background theory	hypothesis
1	Transient blurring and doubling are allegedly symptoms of SSS	Transient blurring and doubling are more prevalent in the dyslexic group
2	The above finding has been attributed to binocular or accommodative dysfunction	The presence of these symptoms is associated with the results of binocular vision & accommodative tests
3	SSS may be synonymous with pattern glare	The presence of these symptoms is associated with the pattern glare test results
4	Those who suffer from repetitive headaches are more susceptible to pattern glare	There is an association between pattern glare and the incidence of headaches in both groups
5	There is a greater incidence of auto-immune disorders in dyslexia	There is an increased history of allergies (including asthma) in the dyslexic group
6	There is a relatively high incidence of genetically-related cortical focal dysplasias in dyslexia	There is an increased family history of epilepsy in the dyslexic group
7	Dyslexia and the conditions in 4-6 share a common aetiology	There is a link between left handedness, repetitive headaches, history of allergies, and pattern glare in the dyslexic group.
8	Binocular vision anomalies occur more often in dyslexia	There is an increased history of binocular vision problems in the dyslexic group

Table 5.1 Hypotheses relating to symptoms and history, and the theoretical basis for these. "SSS" is scotopic sensitivity syndrome.

5.3.2.2 Ophthalmoscopy and Ocular Motility

There have been no suggestions of increased ocular pathology in dyslexia, and no specific hypotheses concerning the ophthalmoscopic findings were investigated. Similarly, no specific hypotheses concerning extra-ocular muscle incomitancy were proposed.

5.3.2.3 Basic Refractive Tests

In the present research, V/A (V/A) is used to refer to that which is obtained when the subject wears the refractive correction, if any, that is normally used in class. This criterion was chosen because it relates to the normal reading situation for each subject, but has the disadvantage that V/A will in various cases refer to appropriately or inappropriately corrected or uncorrected acuities. It was concluded from Section 2.3.1 that most studies had found distance V/A to be normal in dyslexia, although near V/A may be impaired; this was investigated in the present research. Pickwell (1989, p. 42; 1991) noted that better monocular than binocular V/A is a sign of decompensated heterophoria; this was also investigated. In addition to the main hypothesis concerning refractive error, that there would be increased hypermetropia in the dyslexic group, the incidence of anisometropia and astigmatism were also investigated.

5.3.2.4 Binocular Vision and Orthoptic Tests

The main hypotheses in this section were that there would be an increased incidence of heterophoria (mainly exophoria at near) and a relatively remote near point of convergence in the dyslexic group. It has been suggested that binocular instability (Holland, 1987), poor vergence control (Stein et al., 1988), and unstable binocular control (Bedwell et al., 1980; Stein, 1991a) occur more often in dyslexia. These conditions might be expected to result in an unstable measurement with a dissociation test; this was investigated.

Since the resting point of convergence is usually situated at a distance of approximately 1 m (Owens and Leibowitz, 1983, pp. 30-37), vergence dysfunction could manifest as a relative inability for the eyes to diverge or converge from this point, and this may account for the finding of increased esophoria at distance and exophoria at near in dyslexia (Mayou, 1962; Dunlop and Banks, 1974). The following additional hypotheses therefore were included: that the dyslexic group would exhibit relatively more esophoria at distance and exophoria at near and reduced vergence amplitude.

It has been suggested that a sensitive measure of near stereopsis might be a useful screening test for binocular and accommodative dysfunction (Walraven, 1975); the uncertainty in the literature on stereopsis tests and dyslexia may be due to the relative insensitivity of many of the tests that have been used (Reading, 1983, pp. 173-191). It was therefore hypothesised that the stereopsis of the dyslexic group, when measured with a sensitive test, would be reduced relative to that of the control group.

5.3.2.5 Tests of Accommodation

The main hypothesis in this section was that there would be a reduced amplitude of accommodation in the dyslexic group. This hypothesis was further investigated with other, more functional, tests.

5.3.2.6 Modified Dunlop Test

In view of the literature reviewed in Section 3.3, the hypotheses that a stable referent eye is less well established in the dyslexic group, and that this may be linked to vergence dysfunction (Fowler et al.; 1988) were investigated.

5.3.2.7 Pattern Sensitivity

Many studies were reviewed in Section 4.2.2 that had evaluated the effect of tinted lenses on reading performance; it was shown that this type of paradigm is severely limited by an inability to control for the placebo effect. The theory concerning pattern glare (*see* Section 4.4.2) not only provides a long-overdue feasible hypothesis for this therapy, but also a potential for controlled investigation. The hypothesis that pattern glare is more prevalent in the dyslexic sample was therefore investigated.

5.3.2.8 Investigations of Parallel Visual Processing

The existence of parallel visual pathways in the visual system and the evidence for a transient system deficit in dyslexia were discussed in Section 2.7.1. It was noted that the 3 main methods that have been used to assess transient system function in dyslexia were measures of visible persistence, the spatial contrast sensitivity function (SCSF), and the temporal contrast sensitivity functions (TCSF). One aim of the present study was to compare the results of 2 of these tests and, in view of the criticisms noted in Section 2.7.1.7 concerning the tests of visual persistence, paradigms based on the SCSF and TCSF were chosen. An interesting finding by Merigan and Maunsell (1990), which suggests that the SCSF does not measure transient system function (*see* Section 8.3.7.4), further increases the importance of investigating the relationship between the results of these 2 tests in dyslexia. Finally, Lovegrove et al. (1982) found a decreased SCSF at low spatial frequencies in children with a specific RD (SRD), but a normal (or possibly slightly enhanced) SCSF at high spatial frequencies. Since the task for the child in this test is essentially the same at all spatial frequencies, the high frequency response can act as a control for attentional or criterion differences between the 2 groups. The main hypotheses, therefore, were that the dyslexic group would show an impaired low spatial frequency SCSF and TCSF.

It has been suggested that the transient visual system may be important in the feedback mechanism responsible for the control of vergence (Stein, 1991a) and accommodation (Mathews and Kruger, 1989); although in the present state of knowledge such a link can only be extremely tentative (*see* Section 9.2.2). The hypothesis that binocular and accommodative dysfunction would be associated with impaired performance at the "tests of transient system function" was investigated. If pattern glare is unusually common in dyslexia then it could be explained in terms of a transient system deficit (*see* Section 4.4.4; this hypothesis was also investigated.

5.3.2.9 Visual Search Task

It was hypothesised that the dyslexic group would be slower at the visual search task, and that the subjects with vergence dysfunction, or an unstable reference eye, would have relatively worse performance at the binocular condition of this test. Some aspects of the VST design allowed further hypotheses concerning pattern glare and saccadic programming in dyslexia to be investigated; these will be discussed in the appropriate sections on methods and analyses.

5.4 TESTS OF INTELLIGENCE

5.4.1 Introduction

One point that was clear from the literature review is that research investigating correlates of dyslexia should control for the effect of intelligence. The validity and usefulness of measuring intelligence has long been the subject of dispute (Howe, 1990), although most agree that intelligence tests do play a valuable role in modern psychology (Nettelbeck, 1990). Two tests of intelligence were used in the present research, one of which is administered on an individual basis, and one that can be administered on a group basis; these will now be described.

5.4.2 Description of Tests Used in Present Research

5.4.2.1 The Wechsler Intelligence Scale for Children (Revised) (WISC(R))

The WISC(R) is an untimed individual intelligence test for the age-range 6-17 years (Wechsler, 1974). It was partly constructed from the Wechsler-Bellevue test, which was also the precursor of the widely used Wechsler Adult Intelligence Scale (Wechsler, 1955). The WISC(R) consists of 12 subtests in 2 scales.

Verbal Scale	Performance Scale
general information	picture completion
general comprehension	picture arrangement
arithmetic	block design
similarities	object assembly
vocabulary	coding
(digit span)	(mazes)

Raw scores on each subtest are converted into scaled (age-related) scores and combined (minus digit span and mazes) to give verbal, performance, and full-scale IQs.. Butcher (1975, pp. 230-231), in his selective survey of IQ tests, stated that the reliability of the whole test was high, although there was a lack of predictive validity for subsequent behaviour, and he felt that there was little evidence for the sound use of WISC difference scores (e.g. verbal IQ minus performance IQ).

5.4.2.2 Ravens Progressive Matrices (RPM) and Mill Hill Vocabulary Scale (MHV)

The Standard Progressive Matrices (Raven et al., 1988a, b) is an untimed test that can be used on a group basis and comprises 60 individually presented tests (Sweetland and Keyser, 1983, p. 33). Each of these consists of a design or matrix from which part has been removed. The subject has to examine the matrix and decide which of 6 alternatives is the correct one to complete the matrix; there are 12 tests in a "set" and there are 5 sets, lettered (a) to (e). The first problem in each set is designed to be self-evident, and the subsequent tests become increasingly difficult. Each set develops one of the following themes: (a) continuous patterns, (b) analogies between pairs of figures, (c) progressive alterations of patterns, (d) permutations of figures, and (e) resolution of figures into constituent parts.

In addition to the Standard RPM there is also an easier "coloured" version and an advanced version. Burke (1958) provided an early but useful review of the use and limitations of these tests. The standard RPM (1985 reprint) was used in the main study, although this has changed little since the original 1938 version (Raven et al., 1988a). Full details of the design, use, standardisations, reliability, validity, scoring, and interpretation of this test were given by Raven et al. (1988a). Shaw (1967) stated that the test had been well established by previous research as an instrument with considerable reliability.

The MHV test can be used on a group basis and includes 88 words, divided into two parallel series of 44 words, known as set A and set B. Each set consists of words that become progressively harder for the child to identify. Set A was used in the main study in an open-ended form; the subjects wrote a short definition next to the appropriate word on the answer sheet. Set B has a multiple choice format; the subject underlines the most likely synonym from 6 alternatives. In the present study the test was administered immediately after the RPM, without a time limit, and as suggested by Raven et al. (1988b). Full details of the standardisation, reliability, validity, administration, and scoring were given by Raven et al. (1988b).

5.4.2.3 The Relationship Between Scores on The WISC and RPM Tests

In the main study the experimental group, whose IQ was measured with the WISC(R) test, was matched with a control group whose IQ had been measured with the RPM and MHV tests. The theoretical and experimental evidence to support this matching will now be discussed.

Theoretical Evidence

Butcher (1975) summarised the rationale behind the WISC, that was based upon Wechsler's definition of intelligence: "the aggregate or global capacity of the individual to act purposefully, to think rationally and to deal effectively with his environment". For the RPM, Heim (1970) reported that Raven used a literal definition: "according to the Oxford Dictionary, 'intelligence' may mean either 'understanding as a quality admitting of degree' or 'a piece of information'." Raven elaborated as follows: "The two meanings of the word are equally important. In order to act intelligently in any situation, a person needs both the necessary information and the capacity to form comparisons and reason by analogy." This then is the basis of Raven's tests: the Mill Hill vocabulary measures the information a person possesses whilst the progressive matrices measures his reasoning power; Raven (1990a) described these as a person's reproductive and eductive abilities respectively.

For the age group in the main study, Weschler (1974) quoted correlation co-efficients of 0.64 to 0.73 between the verbal and performance IQs in the WISC(R) test. Raven (1981) found lower correlations (0.50 to 0.57) between the RPM and the MHV scores, and Raven (1990a) pointed out that it is inappropriate to average the RPM and MHV results, and that verbal IQs in dyslexia may be misleading. Hence, from a theoretical and pragmatic standpoint, the best method may be to match the RPM score with the WISC(R) performance IQ.

Experimental Evidence

Considering the widespread use of both tests (Butcher, 1975, pp. 231 and 239), there has been surprisingly little research that directly examined the relationship between the RPM and WISC(R) in English-speaking populations (Raven 1988; Raven and Court, 1989), although the progressive matrices test in isolation has been shown to correlate reasonably well with a number of other IQ tests (Walton, 1955; Zimmerman and Woo-Sam, 1973). Shaw (1967) found a high correlation ($r = 0.83$) between the RPM and the WAIS; this paper lacked procedural and statistical details.

Birkemeyer (1964) investigated the relationship between the coloured progressive matrices (CPM) (1960 version) and the WISC. In a group of 46 children who were aged 7 to 11 years, had a mean FSIQ of 94, and all spoke English as their first language, she found highly significant Spearman correlations ($p \leq 0.001$) between the CPM and the FSIQ ($r = 0.62$), WISC verbal IQ ($r = 0.55$), and the WISC performance IQ ($r = 0.66$). In a further study, Birkemeyer (1965) found that 28 "Anglo" children with a mean WISC full-scale IQ of 91.0 showed a high correlation between the CPM and the full-scale IQ (Spearman rho 0.50, $p < 0.01$) and the performance IQ (Spearman rho 0.70, $p < 0.01$), but a poor correlation with the verbal IQ. A second group of children of Spanish or Negro origin, that was matched to the first group for age, sex, and full-scale WISC IQ, showed correlations that were similar, but slightly higher.

Hoffman (cited by Raven, 1990a) found a high correlation between the RPM and WISC performance ($r = 0.70$) and full-scale ($r = 0.62$) IQ, but a relatively low correlation with the WISC verbal scale ($r = 0.52$) in Arizona public schools (few details of the sample were given). Pearce (1983) investigated the relationship between the WISC(R) and RPM scores for 29 "gifted children" (with results in a test of academic aptitude in the top tenth percentile), aged between 10 and 12.5 years. The highest correlation of the RPM test was with the full-scale WISC(R) IQ ($r = 0.50$), then the performance IQ ($r = 0.42$), and then the verbal IQ ($r = 0.38$); all these correlations were significant ($p < 0.005$). Some studies with non-English speaking subjects have found similar correlations between the RPM and WISC full-scale IQ (Raven and Court, 1989), and Mehrotra (1968) examined the relationship between RPM and WISC scores on 45 (presumably) English-speaking children in India. The correlation co-efficients were 0.68, 0.61, and 0.60 for the RPM and the WISC full-scale, performance, and verbal IQs respectively; all of these were significant at the 0.01 level.

Raven et al. (1988a) concluded from the literature that moderate to high correlations are reported for the SPM and various non-verbal and performance intelligence tests for use with children, but correlations with verbal intelligence and vocabulary tests tend to be slightly lower, generally falling below 0.7. Hence, for group matching, it would seem appropriate from a theoretical and experimental point of view to match WISC(R) performance IQ with the RPM result, without taking into account the MHV score. This approach was verified by Raven (1990b), and Wechsler (1974) showed that the WISC(R) performance IQ is closely correlated with the full-scale IQ (r = 0.90 to 0.92).

Precedents

Table 5.2 shows the main methods of matching used by other researchers of visual factors in dyslexia; many studies did not give precise details. There does not appear to be any consensus over which measure of IQ is the most appropriate to control for in matched group studies (Stanovich, 1991), although the majority of studies in Table 5.2 used full-scale or performance IQ. Stein (1989a) stated that full scale WISC IQ should not be used to match groups in research on visual aspects of dyslexia. He thought that the verbal components of this test would penalise poor readers disproportionately.

name of researchers	year	description	IQ test used for matching
Park & Burri	1943	optometric factors	unclear
Drasdo	1972	optometric factors	WISC PIQ
Létourneau et al.	1979	convergence	unclear, ? school grades
Poynter et al.	1982	oculomotor functions	VIQ (Peabody)
O'Grady	1984	optometric factors	VIQ (Peabody)
Aasved	1987	optometric factors	not given
Stein and Fowler	1985	referent eye	BAS
Stein	1988	re-analysis of above	PIQ controlled for
Stein et al.	1989	review of their work	non-verbal subtests of BAS
Bishop et al.	1979	orthoptic status	WISC(R) FSIQ
Newman et al.	1985	Dunlop test	WISC(R) verbal & performance
Lovegrove et al.	1980a	visual persistence	matched but not given
Lovegrove et al.	1980b	CSF	matched but not given
Lovegrove et al.	1982	CSF	RPM
Lovegrove et al.	1986	review	non-verbal IQ (average or above)
Martin & Lovegrove	1987	flicker	RPM
Martin & Lovegrove	1988	flicker masking	RPM
Williams & Bologna	1985	perceptual grouping	not given
Williams et al.	1987	visual search	not given
Williams et al.	1989	masking	WISC(R)
Williams et al.	1990	masking	WISC(R)
Pavlidis	1981b	eye movements	matched but not given
Pavlidis	1985	eye movements	WISC or RPM (loosely matched)
Adler-Grinberg & Stark	1978	eye movements	not matched

Table 5.2 The IQ tests by the main investigations of visual aspects of dyslexia to match groups or control for intelligence. The "description" column describes the general nature of the study; "BAS" is British Ability Scales and "FS" is full-scale, "PIQ" and "VIQ" are performance and verbal IQ respectively (other abbreviations are explained in the text).

5.4.2.4 Units For The Measurement of Intelligence

One of the main criticisms of the use of tests of intelligence in the past has been the use of intelligence quotients (Butcher, 1975, p. 217). Traditionally, the results of intelligence tests were used to obtain a "mental age", that is the age at which an "average person" would have obtained the same score as the testee. The IQ was then derived according to the following formula:

$$IQ = 100 \times \frac{\text{mental age}}{\text{chronological age}}$$

The calculation of quotients by this method is undesirable for several reasons, most notably that it is difficult to achieve an equal spread or dispersion of quotients at different ages (Butcher, 1975, p. 217). Most modern versions of intelligence tests use different scoring methods to avoid these problems.

The recommended scoring method for the RPM and MHV tests (Raven et al., 1988a) is to convert raw scores to percentile ranks (the percentile rank indicates the percentage of scores in a distribution that lie below any particular score; Cohen and Holliday, 1982). Tables, that are based on normative data, are provided for each age group (Raven, 1981; Raven et al., 1988a, b; Raven, 1990a). The advantage of the percentile ranking is that it is easily interpreted and is less open to misuse. Disadvantages of this system, that locates observations relative to the sample as a whole (McGhee, 1985), are that it is difficult to relate the results to standard IQ values (Zimmerman and Woo-Sam, 1973) and it does not lend itself to statistical analysis. To elaborate on this latter point, since percentile scores form a non-linear scale on the x-axis of the normal distribution graph, 2 different percentile scores cannot be averaged to give a combined score.

Wechsler overcame the problems traditionally associated with IQ's by using "deviation IQ's". This term is really a misnomer, since these are not quotients but are scores scaled to give a particular mean and deviation. In the case of the WISC(R) test these are scaled to give a mean of 100 and a standard deviation of 15 for each age group (Butcher, 1975, p. 217-218). This system, which resembles standard z-scores, differs from percentiles in describing the location of observations relative to the mean in units that are a multiple of standard deviations. Deviation IQ's are therefore a linear scale on the normal distribution graph, and hence lend themselves to statistical analysis. The norms that were used in the present research are detailed in Section 7.2.1.

CHAPTER 6
PILOT STUDY

6.1 INTRODUCTION

The pilot study was a blind, randomised study of a group of children, most of whom had learning difficulties (mainly dyslexia), to investigate the relationship between their optometric and psychometric profiles. The aims were to investigate the ophthalmic correlates of reading disability in a heterogeneous group of children and to determine the most useful tests and areas for detailed investigation in the main study using, wherever possible, clinical tests.

6.2 METHOD

6.2.1 Subjects

The subjects were 10 children who had been referred from several sources to Dr Ian Richards, a child psychologist, owing to a suspected learning difficulty. Throughout the study he referred all the children he assessed to the optometry clinic, and those who met the following criteria were included in this research:

(i) aged between 8 and 15 years
(ii) WISC (R) full-scale IQ within the normal range
(iii) able to complete a full eye examination and psychological assessment.

6.2.2 Psychometric Testing

The psychometric testing was carried out by Dr Richards at Sutton Coldfield Dyslexia Institute, Aston House Dyslexia Trust (Worcester), and Aston University; and included the tests listed in Table 6.1.

parameter	test
full scale IQ	WISC (R)
verbal IQ	WISC (R)
performance IQ	WISC (R)
graded word reading	Schonell
reading accuracy	Neale
reading comprehension	Neale
reading rate	Neale
graded word spelling	Vernon
auditory sequential memory	WISC digits
visual sequential memory	ITPA

Table 6.1 Tests comprising the psychological assessment.

The WISC(R) was described in Section 5.4.2.1, and was used in the normal way (Wechsler, 1974). The degree of reading retardation was calculated using Yule et al.'s

1984 equation (cited by Thomson,1984); this was derived from a large population and is described more fully in Section 7.2.2.1.

The Schonell Graded Word Reading test (Schonell, 1942) is an untimed test in which the child is required to read aloud a series of words, graded in difficulty; the accuracy is scored to obtain a "reading age" (Newton and Thomson, 1977). The Vernon Graded Word Spelling Test is an untimed test in which words, graded in difficulty, are read to the child, with contextual references. The subject writes the words down, and his accuracy is scored to obtain a "spelling age" (Sweetland and Keyser, 1983, p. 221).

The Neale Analysis of Reading Ability consists of 3 parallel forms, each containing reading passages standardised for 6 different grades (Sweetland and Keyser, 1983, p. 500). The test is printed in 3 different sizes of type, and for each passage there is a drawing that sets the scene for the passage to be read. Subjects are scored for speed and accuracy during the reading, and for comprehension by questions at the end; British equivalent reading ages are given for each raw score. The second edition of the test was used (Neale, 1980).

Auditory sequential memory was assessed with the digit span subtest from the WISC(R) test. A series of digits (one-figure numbers) are read out that increase in complexity from 3 numbers in each series to 5. In the first part, the subject is required to repeat the series, in the second part to repeat it backwards (Butcher, 1975, p. 226). Visual sequential memory (VSM) was assessed with the VSM sub-test of the Illinois Test of Psycholinguistic Abilities (Sweetland and Keyser, 1983, pp. 586-587). The child is shown a series of symbols which are then covered and he has to select the correct symbols from 15 alternatives and arrange these in the appropriate order; the number of symbols in each series increases in complexity from 3 to 5 (Kirk et al. 1968).

6.2.3 Optometric Routine

At the time of the eye examination, the author was unaware of the nature of the children's disability, or of any results from the psychological assessment. This blind protocol was only broken after the written report of the eye examination had been completed and sent to the appropriate parties.

The optometric examination was carried out in the optometry clinic of the Vision Sciences Department at Aston University, and included the tests listed in Table 6.2. In all cases one or both parents were present during the examination. None of the subjects used spectacles.

symptoms and history	1
ophthalmoscopy and pupil reactions	14
basic refractive tests	
distance visual acuities	2
near visual acuities	5
retinoscopy	12
subjective refraction and visual acuities	13
binocular vision and orthoptic tests	
cover test	3
dissociation test	7
near associated heterophoria	9
near point of convergence	4
AC/A ratio	8
foveal suppression	10
prism vergences at near	18
stereopsis	11
tests of accommodation	
amplitude of accommodation	6
accommodative lag	15
Dunlop Test	
modified Dunlop Test	16
alternative Dunlop Test	17
pattern sensitivity	20
visual search task	19

Table 6.2 Tests comprising the optometric examination. The numbers signify the order in which the tests were carried out.

6.2.4 Symptoms and History

The subjects and their parents were asked questions on the following topics, most of which are covered at a normal eye examination (Ball, 1982): whether any refractive correction was or had previously been worn; clarity of distance and near vision, including details of any transient blurring; presence of any episodes of diplopia; details of headache (type, location, onset, severity, duration, frequency, and any associated factors); general health; medication; relevant personal medical history (including episodes of asthma or other allergies); and family ocular or medical history (all subjects were asked whether there was any family history of epilepsy or migraine). Patients were not asked any questions about their schoolwork, the psychological assessment, or any details of a learning difficulty, and these subjects were positively avoided if brought up by the child or parents.

6.2.5 Ophthalmoscopy

Direct ophthalmoscopy was carried out to assess ocular health and the integrity of the fundus. Pupil reactions (direct, indirect, consensual, and afferent) and ocular motility were also checked.

6.2.6 Refractive and Miscellaneous Tests

6.2.6.1 Distance and Near Visual Acuities

The monocular distance unaided V/A was measured on an internally illuminated (240 cdm^{-2}), 83% Michelson contrast, standard Snellen letter chart at 6 m. A chart with a rotating octagonal drum of concealed lines was used to prevent the patient learning the chart. V/As were recorded as a Snellen fraction, but were subsequently converted to decimal V/As. With this system 1.00 represents "normal" V/A, where the minimum angle of resolution (equivalent to one limb of a typical test letter) subtends 1 minute of arc (O'Leary, 1988). If the smallest letter that a person could read was twice this size, his decimal V/A would be 0.5; if he could resolve a letter that was half the normal size, his decimal V/A would be 2.0. The smallest line on the chart that was used in this study represented a V/A of 1.2. Monocular near V/As (unaided) was assessed on an externally illuminated (115 cdm^{-2}) reduced Snellen chart (the reduced Snellen chart provided with the RAF rule was used at 33 cm), where the smallest line was equivalent to a V/A of 1.0.

6.2.6.2 Retinoscopy

Retinoscopy is an objective method of determining the refractive error of the eye by observing the movement of light reflected from the patients fundus (Henson, 1983, pp. 14-24). Lenses are adjusted whilst the patient fixates a target until "neutrality" of the reflex is obtained (Taylor, 1988). A trial frame and lenses were used, and conventional static distance retinoscopy was employed (Taylor, 1988) with the patient fixating an appropriate Snellen letter at 6 m. The spherical component of the refractive findings at neutrality was adjusted for the working distance (66 cm) by subtracting 1.50 D.

6.2.6.3 Subjective Refraction

A conventional monocular subjective refraction was carried out to determine the refractive error (O'Leary, 1988) using a trial frame and lenses, and the corrected monocular V/As were recorded. A cross cylinder technique was used to measure any astigmatism (Emsley, 1977, pp. 146-150) and the refraction was checked with the +1.00 D blur test (Bennett and Rabbetts, 1984, p. 99). The negative cylinder notation is used to quantify astigmatism throughout the present research, and the spherical equivalent refractions (SER's) were calculated by adding one half of the cylindrical component to the spherical component.

6.2.7 Binocular Vision Tests

6.2.7.1 Cover test

The cover test detects any active or passive deviation of the visual axes (Millodot, 1986). The unilateral (objective) cover test was used, in which the subject fixates a target and one eye is covered for 1 or 2 seconds, the cover is removed for a few seconds, the other eye is covered, and so on. If one eye has an habitual deviation of its visual axis (i.e., a strabismus) then it will, when the non-deviating eye is covered, turn to take up fixation. The degree of this movement can be gauged by the examiner and the angle of the strabismus thus estimated. If a heterophoria is present, then the eye behind the cover will deviate to take up its preferred position in the absence of a stimulus to fusion (this is the passive position). When the cover is taken away, this eye will move to re-fixate the target; this movement can be used to estimate the magnitude of the heterophoria.

The cover test was carried out without refractive correction at distance (6 m) and near (30 cm). The distance target was a Snellen letter from the line above the worst monocular V/A, and the near target was black line measuring approximately 4 mm by 0.5 mm. Any heterotropia or heterophoria was estimated by observation to the nearest 1 prism dioptre (1 prism dioptre = 1 $\Delta = 0.57°$; Bennett and Rabbetts, 1984, p. 12).

6.2.7.2 Dissociation Test

Dissociation tests measure a heterophoria by presenting images to the 2 eyes that are so dissimilar that they cannot be fused (Millodot, 1986). The Maddox Wing, a near dissociation test, was used in this study (Lyle and Wybar, 1967, pp. 200-201); this employs a number of septa to dissociate one part of the field from the part seen by the other eye (Pickwell, 1989, p. 33). The subject views a dark card at a distance of 30 cm that has a horizontal scale that, at that distance, is graduated in steps of 1 Δ. The numbers have higher values at each extremity of the row, and decrease to a central zero, with which an adjacent arrow is aligned. The septa are so arranged that one eye views the arrow and the other the numbers. The subject states which number the arrow is pointing at, and the result is recorded as x Δ of exo- or eso- phoria. There is a similar vertical scale and arrow for the measurement of any hyperphoria. The scale for the measurement of cyclophoria was not used in this study.

After 15 seconds adaptation, when the subject was asked to focus on the letters adjacent to the numbers, horizontal and then vertical readings were taken in the normal way (Pickwell, 1984b). If the subject reported that the target position was unstable, then the median position of the target was determined over the next 10 seconds from the patient's description of the numerical range over which the arrow moved. The standard Maddox wing supplied by Clement Clarke International Ltd. was used, and the luminance of the target screen was 5 cdm^{-2}. Results were recorded to the nearest 0.5 Δ.

6.2.7.3 Near Associated Heterophoria

Corresponding retinal points are 2 points, 1 on each retina, that during normal binocular vision receive corresponding images of an object in space and give rise to a single percept (Millodot, 1986); their existence was postulated by Aristotle in the fourth century B.C. and by Descartes in 1637. A point on one retina in fact corresponds with a small area on the other retina; this is called Panum's area, and a consequence of this is that one eye can over- or under-converge by a small amount without losing binocular single vision (Nelson, 1988). Such a movement is called a fixation disparity (Millodot, 1986), and the incidence and magnitude of this may be increased in individuals who have difficulty in compensating for a heterophoria (Mallett, 1988). The strength of prismatic correction that enables a person to eliminate a fixation disparity may therefore be a useful measurement, and this is called the associated heterophoria (Solomons, 1978, p. 398); this is often inappropriately referred to as "the fixation disparity" (Pickwell, 1989, p. 37).

The Mallet Fixation Disparity Unit (Mark 3) was used to measure the associated heterophoria, as recommended by Mallett (1966), without any refractive correction. This instrument consists of a small central fixation letter "X" with an adjacent letter "O" on either side, the 3 letters being seen binocularly. There are 2 green polarized vertical bars (nonius strips) in line with and directly above and below the centre of the X. The subject wears cross-polarized filters so that each eye sees 1 nonius strip, and a fixation disparity will cause a mis-alignment of the strips when the patient views the X. The magnitude of the associated heterophoria is found by placing prisms before the eyes until the polarised strips are brought into alignment. A second test target, identical to the first but rotated through 90°, is used for vertical measurement. Both tests are surrounded by printed text that provides a "peripheral fusional lock"; a "central fusional lock" is provided by the letters OXO; tests that lack this central fusional lock can give different results (Pickwell, 1984a).

The target in this test subtends 2° and the illumination, measured through the polaroid filters, was 24 cdm^{-2}. The horizontal reading was taken first, followed by the vertical, and the results were recorded as the minimum amount of prism to correct any fixation disparity (these were introduced in ascending steps of 0.5 or 1 Δ).

6.2.7.4 Near Point of Convergence

The near point of convergence (NPC) is the nearest point where the lines of sight intersect when the eyes converge to the maximum (Millodot, 1986). The RAF Near Point Rule was used to measure the NPC; this is a rule, one end of which rests against the cheeks, and which has a rotating drum incorporating several targets that can be pushed to or away from the subject.

The standard convergence target on the RAF rule (Clement Clarke International, 1989) was used; this is a black vertical line (2.4 cm long by 0.5 mm wide) with a central black dot (2 mm diameter). The luminance of the target was 115 cdm^{-2} and the rate of movement was approximately 0.5 Δ/second. The subject was instructed that the line may become blurred, but that he should try to keep it single for as long as possible. Once diplopia had been reported, the target was moved away until single vision was regained; this was the recovery point. The results were recorded as the measurement on the ruler (in cm) when one eye was seen to diverge (the objective break point), which eye diverged, and also the recovery point (in cm).

Stein et al. (1988) claimed that dyslexic children only exhibit poor visuomotor control with targets that subtend less than 2-3°. The above measurements were therefore repeated using a small target, comprising one black number (number 2, Helvetica typeface) that measured 0.87 mm and hence subtended 0.0166° at 30 cm, 0.5° at 10 cm, and 1.0° at 5 cm. This was placed centrally on a piece of white card (measuring 5.5 cm horizontally and 5.0 cm vertically) that was stuck on the RAF rule in front of the normal convergence target.

6.2.7.5 AC/A ratio

Traditionally, several "Maddox" components to vergence have been described, including accommodative vergence, which is linked to accommodation (Lyle and Wybar, 1967, pp. 295-297). It was originally thought that the other components (tonic, fusional, and proximal convergence) were not linked to accommodation, although accommodative (and fusional) vergence are now believed to interact with proximal vergence (Hokoda and Ciuffreda, 1983). A certain amount of convergence will therefore be induced by a fixed amount of accommodation, and the AC/A ratio is the ratio of the accommodative convergence in prism dioptres to the accommodation in dioptres (Millodot, 1986).

A gradient method was used to measure the AC/A ratio, where -2.00 D lenses were inserted into the lens holders of the Maddox Wing and, after 15 seconds adaptation, the horizontal heterophoria was re-measured (Mallett, 1988). The AC/A ratio was calculated from the difference between this reading and the dissociated heterophoria without the lenses (Pickwell, 1985).

6.2.7.6 Prism Vergences at Near

If an object at a certain distance is fixated and base out prisms of increasing power are placed before the eyes, so as to induce convergence, 2 effects may be noticed (Solomons, 1978, pp. 187-193). Firstly, those vergence components that can vary independently of accommodation will allow the convergence to increase without the target blurring. When these components have been exhausted, the subject may report a blurring; this is the "blur point" and signifies that the accommodative-linked convergence is now being used to maintain single vision. The blurring will increase, until all the "convergence reserves" have been used up when the subject reports diplopia (the "break point"). If the prism is then reduced, the subject will eventually report single vision once more; this is the "recovery point". The above measurements are described in the present study as the positive prism vergences.

A similar procedure, but using base in prisms to induce divergence, measures the negative prism vergences. Synonyms for prism vergences include (Stidwill, 1990, p. 11): relative vergences, although this is sometimes used to refer to the blur point only; fusional reserves, an undesirable term owing to ambiguity over motor or sensory fusion; fusion amplitudes, also potentially confusing since amplitudes are sometimes used to refer to the difference between positive and negative break points; and binocular ductions (Solomons, 1978, p. 193), although this term no longer seems to be in common usage. Even the preferred terminology of prism vergences (Pickwell, 1989, p. 33) may be criticised since the measurement can be made without varying the prism (e.g., with a synoptophore).

Rotary prisms are prismatic lenses whose power can be varied, and a pair of these were used in a trial frame to measure the prism vergences (Pickwell, 1984b). The subject viewed a target that was a reduced reproduction of Figure 6.1 and at the 30 cm working distance subtended 11.7° x 5.7°, with print size equivalent to 6/9 (0.667). This target was selected after trials had shown that it facilitated detection of blur, whilst also allowing easy detection of diplopia and recovery. The target was illuminated at 115 cdm^{-2}, and the rotary prisms were manually adjusted at a rate of approximately 0.5 Δ/s. The exercising of excessive convergence can reduce the ability to diverge (Pickwell, 1989, p. 33), and negative prism vergences were therefore measured first. The subjects were requested to view the target and report when it became blurred or double, or if "anything else happened".

6.2.7.7 Stereopsis

The Titmus Circles Test (Titmus Optical Company) was used to measure the stereopsis (Rosner and Rosner, 1990). This test has 9 numbered diamonds each containing 4 circles, 1 of which should be seen stereoscopically when polaroid analyzers are worn by the viewer; the stereopsis is derived from laterally disparate right and left eye images. The subject reports, on each diamond, which circle "stands out from the others"; a higher level of stereo-acuity is required for consecutive diamonds.

To increase the sensitivity of the test, and to check against a false response, a working distance of 80 cm, as well as the normal 40 cm, was used; this changes the binocular disparity by the ratio of the distances involved (Reading, 1983, p. 184). Each circle subtends 1.2° at 40 cm and the illumination, measured through the polaroid filters, was 80 cdm^{-2}. Stereopsis was first demonstrated using the "fly" target and a modified procedure was then used for the main test, to prevent the subjects guessing the correct response from the lateral relative displacement of the circles (Cooper and Warshowsky, 1977). This began with the 80 cm condition, starting with the first diamond (equivalent to 200 seconds of stereo-acuity at this distance), and the subject was asked to identify which circle "stood out from the page" until he had made 2 consecutive errors. The last correct answer was taken as the threshold stereo-acuity. The test was then repeated at 40 cm, but starting with diamond number 4 (equivalent to 140 seconds at this distance).

6.2.8 Tests of Accommodation

6.2.8.1 Amplitude of Accommodation

This was measured monocularly (right, then left) and binocularly with the RAF rule in the usual way (Reading, 1988). The text target was placed at a distance of approximately 30 cm, and the subject was directed to a line of print which he could just read at this distance (usually the N5 line). He was asked to keep the print as clear as possible and to report when it became too blurred to be legible. The target was moved in at approximately 0.5 D/second, until he reported blurring, when the response was checked by asking the subject to read some letters. The results were read directly off the dioptre scale of the rule.

6.2.8.2 Accommodative lag

The MEM technique of retinoscopy (Griffin, 1982, pp. 379-381; Cooper, 1987) was used to obtain an objective measure of the accommodative lag. This test records the dioptric difference between the actual focus of the eye and the object of regard, and correlates well with other measures of accommodative lag (Rouse et al., 1982; Cooper, 1987; Eskridge, 1989). The subject binocularly fixates a detailed target on the retinoscope and is asked to keep this clear. Retinoscopy is carried out along the horizontal meridian and lenses are very briefly held in front of each eye to neutralise the retinoscope reflex. Each lens should only be present for a "split second" (Griffin, 1982, p. 380) so as not to disrupt the status of the patient's accommodative and binocular response.

The target used in the present study was the internally illuminated (10 cdm^{-2}) cross of dots incorporated into the Keeler Spot Retinoscope (Keeler, Windsor); each limb of this cross is 6 mm long, and there were 5 dots, each 0.7 mm, in each limb. The working distance was 30 cm.

6.2.9 Dunlop Test

6.2.9.1 Modified Dunlop Test

In the Dunlop Test the eyes are diverged to induce a fixation disparity, and the eye in which the fixation disparity occurs is said to be the non-dominant or non-referent eye. The test is normally repeated 10 times, and if the same eye is the referent eye 8 or more times out of 10 then the dominance is said to be "fixed" (or stable); any other result is described as "unfixed" dominance. The Dunlop Test was reviewed in detail in Section 3.3.

This test was performed as described by Stein and Fowler (1985), using a Clement Clarke model 2052-131 synoptophore, and the small Dunlop Test houses (slides F69 and F70). In these slides the targets subtend 3.25°, and they were illuminated at 100 cdm^{-2}.

6.2.9.2 Alternative Dunlop Test

The synoptophore creates extremely artificial and unnatural viewing conditions (Mallett, 1966) and the fixation disparity test of the near Mallett Unit was therefore used, combined with rotary prisms to produce the divergence, as an "alternative Dunlop Test". The fixation disparity target subtends 2°, which is similar to the 3.25° recommended by Stein and Fowler (1984). A possible confounding variable is the presence of a large peripheral fusional lock in the Mallett Unit test, although this would seem to more closely resemble the normal situation when reading.

As with the normal modified Dunlop Test, this test was repeated 10 times to establish the stability of the reference eye (the one in which a fixation disparity did not occur). Polaroid filters were glazed into normal trial lenses which could be inserted into the trial frame behind the rotary prisms. These were randomly reversed throughout the 10 trials, in the same way as the slides are reversed throughout the normal modified Dunlop Test.

6.2.10 Pattern sensitivity

6.2.10.1 Test Design

When Wilkins et al.'s (1984, experiment 1) subjects viewed a striped pattern that should induce pattern glare they reported the following anomalous visual effects, in descending order of frequency: colours (red, green, yellow, blue), diamond-shaped lattice, shimmer, blurring, dazzle, glare, bending of the lines, fading, blobs, or flickering. Wilkins et al. (1984, experiment 5) quantified these visual effects using a paradigm that appeared to be based on their experiment 1 results; subjects were asked to inspect the grating before answering each of the following questions:

do you see a colour or colours?
do the lines appear to bend?
do the lines seem to blur?
does the pattern flicker?
do the lines wobble or shimmer?
do parts of the pattern disappear and reappear?

Wilkins and Nimmo-Smith (1984) used a similar checklist of illusions: colour, fading of the pattern, blurring, bending of the lines, shimmering, flickering, dots streaming up and down, shadowy lines that were not really there, or any other illusions. The method of quantifying pattern glare in the pilot study was based on the above research, but attempted to limit errors that might result from children responding to the suggestion of an anomalous visual effect.

6.2.10.2 Procedure

The subjects were asked to view a horizontal grating at a distance of 30 cm for 10 seconds. The luminance of the grating was 210 cdm^{-2} and it had the following parameters: laser printed on a circle whose diameter subtended 13.6° and that was mounted centrally on a white card; spatial frequency, 4.2 cycles/°; duty cycle, 50%; and contrast greater than 70%. The subjects viewed a central fixation point (black, 1 mm) and were first asked the open question "What do you see"; the response was scaled as none, mild, moderate or severe objective anomalous visual effects. They were then asked if they saw any "illusions, patterns, or movement of the target"; these were scored as mild, moderate, or severe subjective anomalous visual effects, or unable to look at target.

6.2.11 Visual Search Task

6.2.11.1 Test Design

In each subtest of the visual search task (VST) the subject searched for a single digit number in an array of pseudo-random numbers (Figure 6.1). Several numbers were searched for in turn in each subtest, and the mean of the search times for near perfect accuracy was calculated. If refractive, binocular vision, accommodative, or dominance problems were interfering with a subject's reading performance, then they might also be expected to interfere with performance at the VST. Similarly, the eye movements during this task should be similar to those during reading; this had been confirmed in case studies using eye movement recording techniques. Hence, the search time for near perfect accuracy reflects the subject's ability at a non-verbal simulated reading task.

8097	7818	4338	7031	2835
3557	0753	7711	8885	9652
7495	7820	8101	7447	5660
0797	5322	7947	2529	4406
4861	4486	5282	8433	1707

Figure 6.1 A subtest of the visual performance test (reduced in size). The other subtests were similar, but had different amounts of characters in each block (in the above example there are 4 characters in each "block").

Fisher (1974) described 2 hypothetical processing modes in reading and search. "Peripheral search guidance" was activated during eye movements and detected contours in the periphery, hence directing the visual system where to move the eyes for best acuity on important words and phrases. "Cognitive search guidance" interrogated the high information areas and constructed meaning. His experimental work suggested that, although these processes were complementary, peripheral search guidance had the major role in search, and cognitive search guidance had the major role in reading. The effect of peripheral visual problems was not considered, although Hulme (1981, pp. 24-25) suggested that the type of task used in the present research would detect anomalies of visual perception in retarded readers. Brysbaert and Meyers (1991) stressed that letter stimuli should not be used to assess the functioning of the visual system in dyslexia. He thought that because the linguistic system was immature in dyslexia letter stimuli would cause a "top down" cognitive confounding variable.

Comparisons of mean search times between different subjects are limited by confounding variables such as motivation, concentration, and some psychometric factors (*see* Section 8.3.8.2). These problems can be avoided by using intra-subject comparisons of monocular and binocular performance; used in this way, the test may predict whether a binocular vision or dominance problem would be likely to affect reading performance.

The visual search task (VST) that was used in the pilot study included 5 subtests, with 2, 3, 4, 5, and in the last subtest a random number, of characters in each block. The search numbers were 1, 3, 7, and 0, and the order in which the subjects were asked to search for these in each subtest was randomised. The tests were laser printed in a 12 point Helvetica typeface, the illuminance level was 210 cdm^{-2}, and the arrangement was similar to the VST in Appendix 3.

6.2.11.2 Procedure

The subjects were shown the test, and instructed that they should search for the stated number as quickly as possible, but without making errors, and should only use normal along-the-line reading eye movements (the eye movements were observed to confirm this). Each subject was given adequate practice attempts, when he was asked to search for numbers other than 1, 3, 7, and 0; this was to prevent him from learning the correct response. The complete test was performed twice; once monocularly and once binocularly (the order for these 2 conditions was randomised). The subjects always started with the simplest subtest (pairs of characters in each block) and progressed through with increasing complexity until reaching the subtest with randomised characters in each array.

To simulate the subjects' normal reading conditions, no method of head restraint was used. The average viewing distance was approximately 30 cm, and subjects were asked, whenever necessary, to adjust their position to maintain this working distance. Despite this, some children consistently maintained a small, large, or variable viewing distance.

6.3 Results and Statistical Analysis

6.3.1 Introduction

The raw data are given in Appendix 1. Although some other workers in this field have compared their results with clinical norms (e.g., Atzmon, 1985), this approach has several weaknesses: statistically valid normative data is unavailable for many optometric tests, and even when it is available the psychophysical scaling may be invalid (Pierce, 1977); most optometric normative data for children does not take into account the IQ of the sample (Rubin, 1988); normal test results can vary considerably with subtle differences in test design (Mallett, 1988), and some of these factors may have a differential effect on reading disabled populations (Eames, 1934; Stein et al., 1988); and clinical norms are often based on the likelihood of an abnormality being associated with symptoms and may fail to detect a significant departure from the normal mean level of performance (e.g., Létourneau et al., 1979, and O'Grady, 1984, simply described any NPC more remote than 10 cm as "abnormal").

For these reasons, and in view of the heterogeneous nature of the subject group, the main aim of the statistical analysis was to establish whether any of the optometric parameters, either individually or in combination, were correlated with the degree of reading retardation. Another aim was to confirm the significance of any such correlations by controlling for the potential confounding variables of intelligence and age.

6.3.2 Descriptive Statistics

6.3.2.1 Psychometric Data

subject	sex	age	rdg. retard.	FSIQ
PN	male	107	29.5	111
AK	male	136	1.2	108
MW	female	169	16.7	98
LS	male	107	18.9	110
JG	male	109	23.6	115
TA	male	105	-3.6	118
CB	male	110	2.9	108
CW	female	124	17.4	93
LK	female	144	24.5	89
RB	male	181	15.2	92

Table 6.3 Summary of pilot study psychometric data. "age" is chronological age in months, "rdg. retard." is the degree of reading retardation in months (a negative value indicates that the subject read better than was expected from his age and IQ), and "FSIQ" is full scale IQ (WISC-R) in deviation IQ points.

Table 6.3 shows that full scale IQs were within or above the average range, the mean age was 10 years 9 months, and 3 subjects read to a level commensurate with their age and IQ whilst the rest had varying degrees of reading disability, from 15 to 30 months.

6.3.2.2 Refractive, Accommodative, and Miscellaneous Tests

In view of the relatively small number of subjects and the vague nature of reports of symptoms and history (Ball, 1982, pp. 7-26), the data for these variables were not analysed. All findings relating to ophthalmoscopy were normal.

The difference between the right and left unaided visual acuities only varied slightly within the sample, and these data were not analysed. Similarly, the astigmatism, as measured by subjective refraction, only varied from 0 to 0.75 D; and the anisometropia, which was calculated as the difference between the right and left subjective SERs, ranged from 0 to 0.50 D; neither of these parameters were statistically analysed. The right eye accommodative lag was always within 0.50 D and in all but one case within 0.25 D of that of the left eye; the mean of the right and left eyes accommodative lag was therefore used in subsequent analyses.

The pattern glare results were scored on the assumption that the presence of anomalous visual effects that were reported without prompting ("objectively") were more significant than those that were reported only when prompted by a list of possible illusions ("subjective"). Within each of these categories, responses were recorded as none, mild, moderate, or severe. The arbitrary method of scoring placed each of these responses as equidistant points, to one decimal place, on a scale from 0 to 10: subject unwilling to look at pattern (objective) - 0, severe objectively - 1.4, moderate objectively - 2.9, mild objectively - 4.3, severe subjectively - 5.7, moderate subjectively - 7.2, mild subjectively - 8.6, and none subjectively - 10. The Dunlop Test results were scored as the number of times out of the 10 trials that the most fixed referent eye was in fact the referent eye; hence, a score of 5 represents the least stable response and a score of 10 the most stable.

The descriptive statistics for the refractive and miscellaneous test results are given in Table 6.4. Several factors influence the results of the visual search task: whether carried out monocularly or binocularly, which digit is being searched for (1, 3, 7, or 0), which sub-test, and practice effects. To obtain the search task values in Table 6.4, the mean search time was calculated for each subject from all his results (i.e., for each digit, in every sub-test, under both monocular and binocular conditions). This value therefore represents the overall performance in this simulated reading task. Other aspects of the visual search task results will be discussed in Section 6.3.4.

parameter	mean	SD	min.	max.
binoc. dist. V/A	0.91	0.15	0.67	1.13
binoc. near V/A	0.89	0.16	0.67	1.00
mean ret. SER	0.77	0.38	0.00	1.25
mean sub. SER	0.33	0.23	0.00	0.75
amp. acc. (binoc.)	12.75	6.62	4.00	20.00
amp. acc. (worst)	9.90	4.54	3.50	15.00
mean acc. lag	1.12	0.49	0.00	1.62
Dunlop	6.90	1.20	5.00	9.00
Dunlop/Mallett	6.20	1.32	5.00	9.00
pattern glare	6.01	2.11	2.86	10.00
VST	180.6	35.4	124.6	227.0

Table 6.4 Summary of pilot study descriptive statistics from refractive and miscellaneous tests. "binoc. dist. V/A" is the unaided binocular distance V/A, in decimal notation; "mean ret. SER" is the mean of the SERs from both eyes, in dioptres, as determined by retinoscopy; "mean sub. SER" is the equivalent as determined by subjective refraction. All subjects were emmetropic or hypermetropic. "amp. acc. (binoc.)" is the binocular amplitude of accommodation; and "amp. acc. (worst)" is the worst monocular amplitude of accommodation; "mean acc. lag" is the mean of the accommodative lag for each eye. The row for the "Dunlop" test refers to the synoptophore version of this test; "Dunlop/Mallett" refers to the Mallett Unit version of the test. (*See* text for further explanations).

The expected amplitudes of accommodation for a given age can be calculated from the Hofstetter formulae (Reading, 1988):

Minimum amplitude (D) = 15.0 - (0.25 x age in years)

Probable amplitude (D) = 18.5 - (0.3 x age in years)

Applying these formulae to the children in the present study, the minimum expected value is 11.25 D and the anticipated mean amplitude is 15.3 D. The results in Table 6.4 therefore indicate unusually low amplitudes of accommodation in the present sample.

6.3.2.3 Binocular Vision and Orthoptic Tests

The only anomaly to be identified with the distance cover test was 5 Δ of exophoria in subject JG, and the results from this test were therefore not statistically analysed. Similarly, vertical heterophorias were not analysed: none were detected with the cover test, the only dissociated hyperphoria was of 0.5 Δ for subject AK, and the only associated hyperphoria was of 0.5 Δ for subject LS.

The data for the near point of convergence were linearised by converting from centimeters to prism dioptres using the following formula (Bennett and Rabbetts, 1984, p. 162):

$$\Delta = b / d$$

where: Δ = convergence in prism dioptres
b = half the inter-pupillary distance, in centimeters.
d = distance of the object from the centre of rotation of the eye in metres.
The centre of rotation of the eye was taken as lying 1.46 cm behind the cornea (Emsley, 1977, p. 355), and the RAF rule was assumed to measure from the frontal plane passing through the cornea.
Kaye and Obstfeld (1989) showed that the mean interpupillary distance for the age-group under investigation was approximately 56 mm, and therefore "b" was taken as 2.8 cm.

The recovery point was similarly converted into prism dioptres, and the difference between this and the break point was calculated and used in the subsequent analyses. The difference between the prism vergence break and recovery points was derived in a similar way. When the stereopsis test was used at 40 cm many of the subjects achieved the test ceiling; hence, only the test results at 80 cm were used in the analyses. The descriptive statistics for the binocular vision and orthoptic tests are given in Table 6.5.

parameter	mean	SD	minimum	maximum
cover test	1.50	1.51	0.00	4.00
dissoc. phoria	2.40	2.91	-1.00	8.00
assoc. phoria	1.15	1.25	0.00	4.00
NPC (large)	32.8	13.0	14.4	47.0
recovery	1.9	2.7	0.0	7.9
NPC (small)	33.1	11.2	12.5	47.0
recovery	2.1	4.8	0.0	13.8
base in blur	6.80	3.82	1.00	14.00
base in break	12.40	7.00	2.00	26.00
base in recov.	3.30	2.36	1.00	9.00
base out blur	14.33	10.69	2.00	30.00
base out break	17.10	9.27	3.00	30.00
base out recov.	2.55	2.52	0.00	6.00
AC/A ratio	1.25	0.72	0.00	2.50
Stereopsis	52.00	53.91	20.00	200.00

Table 6.5 Summary of pilot study descriptive statistics for binocular vision and orthoptic tests. The following abbreviations were used: "dissoc." is dissociated, "phoria" is heterophoria (negative values represent esophorias; all other values are exophorias), "assoc." is associated, "NPC" is near point of convergence, and "recov." is recovery. The units are prism dioptres, except for the AC/A ratio which is Δ/D and stereopsis which is in seconds or arc.

There is some disagreement concerning the expected "normal" NPC, but most authorities have suggested values between 2 and 10 cm (Dunlop and Banks, 1974; Borish, 1975, p. 204; Bishop et al., 1979; Wick, 1987; and Mallett, 1988), which equate with 81 Δ to 24 Δ in the present study. There is similar equivocality concerning expected results for the prism vergence tests, although most estimates suggest that the base in break point should be at least 12 Δ, and the base out at least 14 Δ (Borish, 1975, pp. 245-252 and 906-914; Wick, 1987; Mallett, 1988). Hence, the results for the NPC and prism vergence tests in

Table 6.5 indicate unusually low vergence amplitude in the present sample. The AC/A ratio results are discussed in Section 6.3.3.

6.3.3 Transformation of Data

Individual optometric tests may not be particularly effective at detecting subtle sub-clinical visual problems. Park and Burri (1943) and Dunlop et al. (1973) overcame this problem by combining the results of their visual tests to obtain a total score of "visual defectiveness". To facilitate the combination of the individual test scores in the present study, the raw data for each optometric parameter was linearly transformed to a score out of 10. This transformation was not a ranking, but used individual formulae for each test that were based on the range of results in the present sample. In all cases 10 represented the best performance (i.e., minimum defect) and 0 the worst raw result.

For most test results the direction of improving performance was obvious, but for some of the binocular vision tests the "rules" that were adopted need clarification. No normative data for the cover test at near could be found and since 4 of the subjects were orthophoric this finding was taken as the optimal score. Borish (1975, pp. 906-914) cited various opinions concerning the normal horizontal finding with near dissociation tests; 2 Δ exophoria was typical and departures from this, both increasing exophoria and relative esophoria, were given proportionately lower scores. For all other measures of heterophoria, orthophoria was taken as the optimal result, and for all measures of prism vergence the highest raw score and lowest difference between break and recovery points represented the optimal values. Clinical norms for the AC/A ratio, as measured in this study, vary from 3 to 6 Δ/D (Mallett, 1988; Wick, 1987; Borish, 1975, pp. 906-914) with most estimates around 4 Δ/D. The maximum value of this parameter in the present study was 2.5 Δ/D, and decreasing values from this were therefore given lower scores.

The transformed scores for the refractive results (the first 7 in the left hand column of Table 6.4) were averaged to give the "refractive score", and similarly the transformed scores for the binocular vision and orthoptic tests (all the variables in Table 6.5) were averaged to give a "binocular function score". The transformed scores for the 2 tests of ocular dominance were averaged to give the "dominance score", and the mean of all the transformed scores from the refractive and binocular vision tests was calculated to give an "eye score".

6.3.4 Correlations of Optometric Results with Reading Retardation

In view of the small sample size and the lack of information concerning the normality of the data, a Gaussian distribution could not be assumed or reliably tested for. Spearman's rank correlation was therefore used to determine the relationship between the degree of reading retardation and the optometric test results described in Tables 6.4 and 6.5 and the combined scores. The correlations were in the anticipated direction (i.e., increasing degrees of reading retardation were associated with decreasing scores) except for those relating to accommodative lag, pattern glare, dissociated heterophoria, base in and out prism vergence recovery, AC/A ratio, and stereopsis. None of these approached significance (2-tailed $p > 0.10$), except for the AC/A ratio (*see* Table 6.6). The most relevant correlations, including all those that approached significance, are given in Table 6.6.

parameter	correlation	
	r_s	p
amplitude of accomm. (binoc.)	-0.68	0.042
amplitude of accomm. (worst)	-0.58	0.082
cover test (horiz. phoria)	-0.52	0.12
NPC (large target)	-0.78	0.019
NPC recovery (large target)	-0.63	0.060
NPC (small target)	-0.75	0.034
NPC recovery (small target)	-0.66	0.084
base in blur	-0.60	0.074
AC/A ratio	0.57	0.088
VST	-0.46	0.087*
Dunlop Test (synoptophore)	-0.44	0.18
Dunlop Test (Mallett Unit)	-0.71	0.032
refractive score	-0.48	0.15
binocular function score	-0.70	0.036
dominance score	-0.85	0.012
eye score	-0.64	0.056

Table 6.6 The results of the Spearman correlations between reading retardation and the most relevant optometric test. "r_s" is the Spearman correlation co-efficient, the 2-tailed (except for * where 1-tailed) significance of which (corrected for ties) is given by the adjacent "p" value. "accomm." is accommodation, "binoc." is binocular, "horiz." is horizontal, and "phoria" is heterophoria.

The results in Table 6.6 show that a higher degree of reading retardation was associated with reduced amplitudes of accommodation and convergence. The highly significant relationship between the near point of convergence, measured with the large target, and the degree of reading retardation is shown graphically in Figure 6.2. The results do not support the use of a small convergence target in place of the normal RAF rule target (cf., Stein et al, 1988) and the finding for the negative prism vergence indicates the possibility of reduced divergent as well as convergent amplitudes.

The AC/A ratio results are puzzling; a higher AC/A ratio is normally associated with convergence excess esophoria (Pickwell, 1989, p. 53); in the present study, where most subjects were exophoric, higher AC/A ratios were associated with greater degrees of reading retardation yet all subjects had relatively low AC/A ratios. It is possible that the -2.00 D lenses that were used to stimulate the accommodation were inadequate, and this possibility is addressed in the main study (*see* Section 7.4.4.5).

The correlation relating to the dominance score reached a much higher level of significance than for either of the dominance tests individually; this may reflect the methodological problems associated with these tests. The Dunlop Test results obtained on the Mallett Unit reached a higher level of significance than those on the synoptophore; this may result from the more natural viewing conditions with the Mallett Unit.

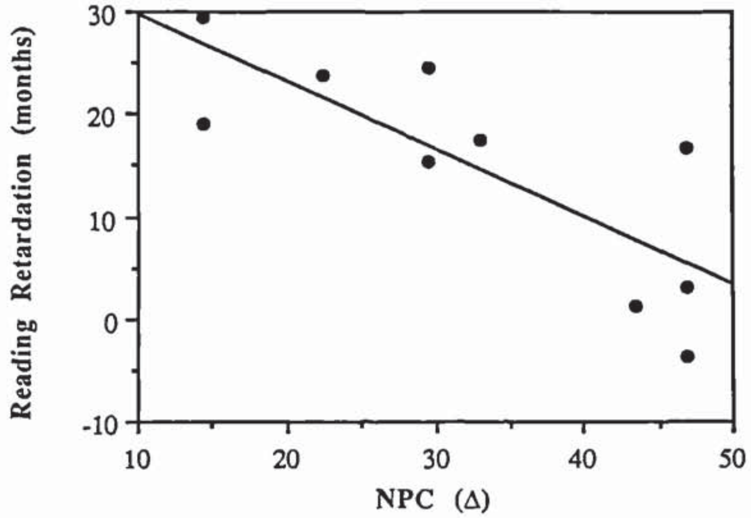

Figure 6.2 Graph of reading retardation v. the near point of convergence (NPC) break point using the large target. Each point represents the results for one subject.

6.3.4.1 Controlling For The Effects of Intelligence and Age

To control for the effect of intelligence, each optometric variable was designated as an x-variable, the reading retardation as the y-variable, and the full-scale IQ as the z-variable. The Kendall correlation co-efficients were calculated for each pair of these variables. The Kendall partial rank correlation co-efficient (Siegel, 1956, pp. 213-229; Cohen and Holliday, 1983, p. 171) is given by:

$$\tau_{xy.z} = \frac{\tau_{xy} - \tau_{yz}\tau_{xz}}{\sqrt{((1 - \tau_{yz}^2)(1 - \tau_{xz}^2))}}$$

where

τ_{xy} = the correlation between variables x and y
τ_{xz} = the correlation between variables x and z
τ_{yz} = the correlation between variables y and z
and $\tau_{xy.z}$ = the correlation between variables x and y when the effect of variable z is partialled out (controlled for)

The Kendall correlation co-efficients for the optometric variables and reading retardation were similar to the Spearman correlation co-efficients in Table 6.6. The Kendall correlation co-efficient between the reading retardation and full-scale IQ was very low ($\tau_{yz} = -0.067$), so when this was partialled out $\tau_{xy.z}$ was very similar to τ_{xy}. In the few cases where $\tau_{xy.z}$ was less than τ_{xy} the difference between the 2 was 0.003 or less. The weak relationship between reading retardation and full-scale IQ may be attributable to the small range of FSIQ in the present sample.

The above procedure was then repeated, but using chronological age as the z-variable. The Kendall correlation co-efficient between reading retardation and chronological age was also low ($\tau_{yz} = -0.067$; by coincidence the same as that for full-scale IQ), and for those variables where $\tau_{xy.z}$ was greater than τ_{xy} the difference between the 2 was 0.004 or less. Hence, it can be concluded that full-scale IQ and age were not significant confounding variables in the pilot study.

6.3.4.2 Visual Search Task

The percentage difference between the mean search times for the monocular and binocular conditions was calculated so that the relationship between this and any binocular dysfunction could be investigated. This was not significantly correlated with the reading retardation or binocular function score (1-tailed $p > 0.10$). A major confounding variable that affected this result was the practice effect; almost invariably the quickest search time was for whichever condition (monocular or binocular) that was carried out last.

A method of contrasts was used to try and isolate the practice effect from the binocular/monocular effect. The mean search time for the binocular condition for those subjects who carried it out first was calculated and called "BF". Similarly, the mean search time for the binocular condition when this was carried out second was calculated as "BS", and equivalent values for the monocular first ("MF") and second ("MS") mean search times were also calculated. The overall size of the practice factor could then be estimated as:

$$\frac{(BS - BF) + (MS - MF)}{2}$$

and the overall size of the monocular/binocular factor as:

$$\frac{(BF - MF) + (BS - MS)}{2}$$

During this calculation it became apparent that 2 further factors were confounding the result. The experimental design was such that the condition to be carried out first had been randomly allocated for each subject; hence, 6 of the subjects performed the monocular condition first, and 4 the binocular. Secondly, the practice effect seemed to be interacting with the monocular/binocular effect. It was felt that these problems, combined with the small sample size, meant that the search task results in this study could not be reliably used to assess the relationship between binocular and monocular performance.

6.3.5 The Interactions Between Optometric Results

The refractive score showed a significant positive correlation with the binocular function score ($r_s = 0.73$, $p = 0.014$, 1-tailed, no ties) indicating that heterophoria (mainly exophoria) and poor vergence amplitudes were linked to hypermetropia and poor accommodation in the present sample. The refractive score did not correlate significantly with the dominance score and there was a positive correlation of border-line significance between the binocular function and the dominance scores ($r_s = 0.43$, $p = 0.10$, 1-tailed, corrected for ties).

The possibility that in some subjects a binocular vision problem occurred together with unstable ocular dominance, and that this was related to reading performance, was investigated by summing the binocular function and dominance scores and correlating this with the degree of reading retardation. This correlation was highly significant ($r_s = -0.88$, $p = 0.0041$, 1-tailed, corrected for ties), and is plotted in Figure 6.3.

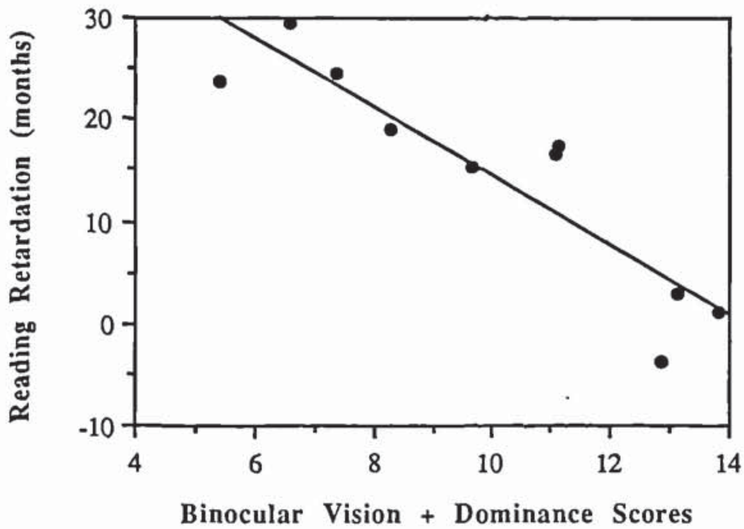

Figure 6.3 Graph of reading retardation v. sum of binocular vision and dominance scores. Each point represents the results for one subject.

6.4 CONCLUSIONS

The size of the sample in the pilot study precludes firm conclusions. The study, however, fulfilled its aim of investigating the most useful tests and areas for detailed investigation in the main study. It was concluded that this should concentrate on binocular vision and accommodative tests, particularly vergence and accommodative amplitudes. There seems no justification for using unusually small targets for convergence testing, and the Mallett Unit seems to be an appropriate alternative to the synoptophore for the Dunlop Test.

During the pilot study several areas were identified where the investigative technique could be improved for the main study. These were: modified designs of near test charts, a distance dissociation test, taking the average of 2 NPC measurements, using a larger stimulus to accommodate in the AC/A gradient test, repeating and averaging the prism vergence measurements, measuring the dynamic performance of convergence and accommodation, using a set pattern for "randomly" reversing the polaroid filters during the Dunlop Test on the Mallett Unit, using a better scoring system for the pattern glare test and including a control grating, reducing the print size in the visual search task, and interweaving the monocular and binocular search conditions so as to control for the practice effect in the same way for all subjects.

CHAPTER 7
MAIN STUDY - METHODS

7.1 AIMS OF THE MAIN STUDY

The aim of the main study was to investigate further the optometric correlates of dyslexia, including pattern glare and the functioning of the transient visual system, in a controlled matched group study. Both groups of children were to be matched for age, sex, intelligence, educational opportunity, and socio-economic background; and were to be examined according to, as far as possible, a blind randomised protocol. It was also planned that the children in the control group should be of at least average attainment in reading and spelling, while those in the experimental group should be sufficiently retarded in reading to meet the normal diagnostic criterion of dyslexia. Finally, all the subjects were required to have average or above average intelligence.

7.2 PSYCHOMETRIC TESTING

7.2.1 Tests of Intelligence

The psychological assessments of the dyslexic group, which were carried out by Dr Ian Richards, included the Wechsler Intelligence Scale for Children (Revised) (WISC-R). This test is a widely accepted and thorough method of measuring a child's intellectual abilities (Butcher, 1975, pp. 229-231), and was described in Section 5.4.2.1. The test is an essential part of Dr Richards' assessment, and some of the data from the test were used for the diagnosis of dyslexia.

The WISC-R test is a "closed" test; it can only be used by qualified psychologists. In order to match the control group as precisely as possible to the dyslexic group it was necessary to obtain a large pool of potential control children whose age, sex, IQ, reading age, and spelling age were known. This required the use of an IQ test which could be administered on a group basis. Additionally, since a psychologist could only be present when half the children were screened, this had to be an "open" test capable of being administered by an optometrist. The most widely used test in the UK that meets these requirements is Raven's Progressive Matrices (RPM) (Vernon, 1962; Butcher, 1975). This was described in Section 5.4.2.2. This test (1988 edition), in conjunction with the Mill Hill vocabulary scale (1985 reprint), was used to screen the control children on a group basis (approximately 30 children in each group) without a time limit, as suggested by Raven et al. (1988a)

Method of Matching IQ Test Scores

The evidence that was reviewed in Section 5.4.2.3 suggests that the most appropriate method is to match the WISC(R) performance IQ with the RPM score. The deviation IQ obtained for the WISC(R) test is based on USA norms (Wechsler, 1974); hence, RPM raw scores were converted to percentile points using the USA norms for the RPM test (Raven, 1990a). In a normal distribution, deviation IQs can be directly (but not linearly) converted to percentile points and Weschler (1974) stated that this was appropriate for performance IQs. Raven (1990a) gave a full table of deviation IQ equivalents for percentile points, and this was used to convert the RPM percentile scores to deviation IQ points, which were used for the final matching with the WISC(R) results.

7.2.2 Tests of Reading and Spelling Performance

The Schonell Graded Word Reading Test and Vernon Graded Word Spelling Test were used to assess all children in the study; the Neale Analysis of Reading Test was additionally used with the dyslexic children. The method of use of these tests was described in Section 6.2.2.

7.2.2.1 Calculation of Reading Retardation

The expected reading age varies with intelligence as well as chronological age, and for statistical reasons will always lie between the chronological age and the age that would be predicted from the IQ. This is called the "regression effect" (Rutter, 1978) and any calculation of reading retardation should take this into account (Rutter and Yule, 1975). The usual method is to employ regression equations that link age, IQ, and reading performance and have been derived from large populations. Several of these were cited by Thompson (1984), including Yule et al.'s 1984 equation, which was based on a "primary school population"; this was used to calculate expected reading age in the main study:

$$\text{expected reading age} = (0.63 \times \text{FSIQ}) + (0.78 \times \text{age}) - 38.86$$

where: expected reading age relates to the Neale accuracy result
FSIQ = WISC(R) full-scale IQ
age = chronological age in months

The difference between the expected reading age and the actual reading age from the accuracy result of the Neale test was calculated as the reading retardation.

7.2.3 Other Psychometric Tests

Several other psychometric tests were carried out on the dyslexic group, including the same auditory and visual sequential memory tests as in the pilot study (*see* Section 6.2.2). Other tests, which were not used in the subsequent analyses, were the assessment of sequencing, knowledge of left/right directions, laterality, a graphomotor test, and an assessment of written expression.

7.3 SUBJECTS

7.3.1 Control Group

The control group was selected from primary schools in the Solihull area. The local education authority helped to select 2 schools with a similar social mix to that normally found in a clinical population of referrals for private assessment of learning difficulties. The following screening tests were used to select the control groups (*see* Section 7.2): RPM, MHV, Schonell Graded Word Reading, and Vernon Graded Word Spelling.

In June 1990 the first school was screened; one class from each year was selected by the teaching staff as being representative and the tests were administered to these classes on a group basis. Those children aged between 7 years 6 months and 12 years 3 months, with RPM and MHV scores at least in the average range, and with reading and spelling ages in excess of their chronological ages were invited to attend the Vision Sciences Department for the optometric assessment. In July 1990 the second school was screened in a similar way; children who met the selection criteria and whose psychometric profiles were likely to facilitate group matching were invited into the department. Approximately a third of the screening at the first school and half of that at the second was carried out by the author.

7.3.2 Dyslexic Group

All the psychological testing was carried out by Dr Richards, and all the optometric testing by the author; this precluded inter-examiner errors. Many local children are referred to Dr Richards at the Aston Dyslexia Consultancy for investigation of suspected learning disabilities, and these assessments take place on the university campus. All the children Dr. Richards saw during the course of the study were invited to participate in the research if they met the following criteria: aged between 7 years 6 months and 12 years 3 months, performance IQ over 85, full scale IQ over 90, and at least 16 months retarded in reading.

7.4 OPTOMETRIC EXAMINATION

7.4.1 Introduction

This was carried out in the Optometry Clinic of the Vision Sciences Department of Aston University, and included the tests listed in Table 7.1. The normal duration of the examination was designed to be 1.5 to 2 hours. Experience with several case studies had demonstrated that a longer session than this often resulted in the subjects' losing concentration, despite rest periods. It was not feasible to persuade control subjects to travel to the department more than once; hence, this time limitation was the main constraint on the quantity and nature of the investigations. If the child became fatigued at any point in the examination a rest period was given.

Unless otherwise stated, all optometric testing was carried out under a combination of normal incandescent and special high frequency (Phillips TLD 32W/84 HF, operated at 28 KHz) lighting. The results were recorded on specially designed record cards. In all cases one or both parents were present for at least some of the examination. The questions asked during the "symptoms and history" section of the examination were designed to investigate hypotheses that often related to other sections of the examination. Hence, although the examination commenced with the symptoms and history, this section will be described last in this and the next chapter.

ophthalmoscopy	20
basic refractive tests	
distance vision	2
near vision	3
retinoscopy	15
subjective refraction and visual acuities	16
binocular vision and orthoptic tests	
cover test (distance & near)	4
near point of convergence	5
dissociation test - distance	14
dissociation test - near	7
AC/A ratio	8
near associated heterophoria	9
binocular status	11
stereopsis	12
relative vergences	19
tests of accommodation	
amplitude of accommodation	6
accommodative lag	18
dynamic assessment of accommodation and convergence	17
modified Dunlop Test	10/13
pattern glare	23
investigations of parallel visual processing	
spatial contrast sensitivity function	21
temporal contrast threshold	24
visual search task	22
symptoms and history	1

Table 7.1 Tests comprising the optometric examination. The numbers represent the order in which the tests were carried out for each subject (to minimise subject boredom, the modified Dunlop Test was carried out in 2 sections).

7.4.1.1 Refractive Correction

For the initial assessment of visual acuities and all binocular vision and accommodative tests glasses were only worn if these were normally used at the appropriate distance in class. The one exception was that where uncorrected myopia was present, the appropriate correction (subjective finding) was worn for the dynamic assessment of accommodation and convergence (both conditions).

7.4.2 Ophthalmoscopy and Ocular Motility

Direct ophthalmoscopy was carried out to assess ocular health and the integrity of the fundus. Pupil reactions (direct, indirect, consensual, and afferent) were also checked at this stage. Binocular ocular motility was assessed in the normal way (Stidwill, 1990), using a 2 mm white dot for fixation.

7.4.3 Basic Refractive Tests

7.4.3.1 Distance and Near Visual Acuities

Monocular and binocular distance V/As were measured as in the pilot study (*see* Section 6.2.6.1). Monocular and binocular near visual acuities were assessed on an externally illuminated (115 cdm^{-2}) chart similar to that designed by Bailey and Lovie (1976); this was a modified EDTRS chart using Sloan letters (The Lighthouse Near Visual Acuity Test, second edition). The chart had 15 lines of 5 letters whose size reduced in a logarithmic progression ("logMAR") of 0.1 log unit per line from equivalent to 6/120 to 6/4.5, at the viewing distance of 40 cm. The Lighthouse Test comprises 2 charts, the first was always used initially on the right eye, the second on the left, and then the first again for both eyes.

7.4.3.2 Retinoscopy

The procedure used was similar to that in the pilot study (*see* Section 6.2.6.2). The fixation target, however, was a green concentric ring at 6 m.

7.4.3.3 Subjective refraction and visual acuities

The procedure was described in Section 6.2.6.3.

7.4.4 Binocular Vision and Orthoptic Tests

7.4.4.1 Cover Test

The objective cover test (*see* Section 6.2.7.1) was carried out at distance (6 m) and near (30 cm). The distance target was a Snellen letter from the line above that corresponding to the worst monocular acuity, and the near target was a letter of a size equivalent to 6/15; if the subject's visual acuity at near was below this level, this letter appeared as a small dot. Any heterotropia or heterophoria was estimated by observation to the nearest 1 Δ.

7.4.4.2 Dissociation Tests

The distance dissociation test that was used in this study employed a Maddox Rod technique. The Maddox Rod (or multiple groove) is a translucent lens that blurs a white spot of light into a red streak, but does not permit form vision (Pickwell, 1989, p. 33). The test is carried out in a darkened room where the subject views a spot of light that is perceived normally by one eye and is seen as a vertical red line by the other eye, which is covered by the Maddox Rod. If the patient is orthophoric, then he should report that the line passes through the spot; if it does not then prisms of various power are placed in front of one eye until the line is coincident with the spot. In this way the horizontal heterophoria (in Δ) can be determined; the Maddox Rod is then rotated through 90° and the vertical reading is taken (Pickwell, 1984b).

A Uniocular Maddox Hand Frame was used (supplied by AIM, model no. 1257); this is a hand-held instrument incorporating a Maddox rod combined with a rotary prism (Lyle and Wybar, 1967, p. 200). This was held in front of the right eye with the prism on 0, and the horizontal and then vertical heterophoria was measured in the normal way (Pickwell, 1984b). If the reading was unstable then the mean of several measurements was calculated; half of these were ascending and the other half descending readings.

The Maddox wing was used for the near dissociation test in the same way as in the pilot study (*see* Section 6.2.7.2). In addition, the subject was asked if the horizontal reading was stable, or if the arrow moved. If he reported that the target was unstable, then the average position of the target was determined over the next 10 seconds, and the degree of variation was noted (e.g., ± 2 Δ). Results, at both distance and near, were recorded to the nearest 0.5 Δ.

7.4.4.3 Near Associated Heterophoria

The apparatus and method was similar to that in the pilot study (*see* Section 6.2.7.3). A record was also made of the stability of the response, both in terms of the type and degree of fixation disparity manifested, and whether one eye suppressed its strip (if so, the degree and frequency of suppression and which eye suppressed were recorded).

7.4.4.4 Near Point of Convergence

This test was carried out with the standard RAF rule target and the same procedure was used as in the pilot study (*see* Section 6.2.7.4. The measurement was repeated so that a mean of 2 readings could be calculated; a third reading was taken when these were significantly discrepant.

7.4.4.5 AC/A Ratio

In the pilot study, -2.00 D lenses were used for the gradient test (Solomons, 1978, p. 257). Mallett (1988) pointed out that the relatively loose relationship between accommodative demand and response can be a source of error with this procedure. A normal accommodative lag of 0.50 D represents a potential 25% error with a -2.00 D lens (c.f., the normal maximum convergence error of 0.8% for a Panum's area of 5'). To reduce this source of error, -3.00 D lenses were used in the main study.

7.4.4.6 Foveal Suppression

If the vergence system is under stress in overcoming a heterophoria then a fixation disparity may be present; the maximum size of this fixation disparity is theoretically limited by Panum's areas, which subtend 5' at the fovea (Mallett, 1988). One way of overcoming this limitation is for one eye to develop subtle foveal suppression. The presence of foveal suppression, therefore, may be a sign of a decompensated heterophoria (Pickwell, 1989, p. 41). Simpson (1991) showed that in binocularly normal subjects the monocular V/A was similar when recorded under binocular and monocular conditions; exceptions would indicate foveal suppression.

Mallett (1966 and 1988) described a polarized test for measuring foveal suppression, and this apparatus was used in the main study. The test resembles an internally illuminated near letter chart which has letters ranging in size from 5' to 20' of arc (at 35 cm) and includes central foveal and paramacular fusion detail. During normal binocular viewing, with a polaroid filter, some of the letters are seen by both eyes, and some by each eye. The conditions of illumination were the same as for the associated heterophoria test.

7.4.4.7 Prism Vergences at Near

The method was similar to that in the pilot study (*see* Section 6.2.7.6), with the following additions. Two measurements of the negative vergences were taken, and if these were significantly different a third was taken. The procedure was then repeated for the positive vergences. The target was a vertical row of 5 numbers (each equivalent to 6/15 (0.4)) on a card which was attached to the RAF rule and at the 30 cm working distance subtended 2° vertically.

7.4.4.8 Stereopsis

The apparatus and procedure was described in Section 6.2.7.7.

7.4.5 Tests of Accommodation

7.4.5.1 Amplitude of Accommodation

The amplitude of accommodation was measured in the same way as in the pilot study (*see* Section 6.2.8.1).

7.4.5.2 Accommodative Lag

The accommodative lag was measured in the same way as in the pilot study (*see* Section 6.2.8.2).

7.4.5.3 Dynamic Assessment of Accommodation and Convergence

Test Design

Whilst tests are routinely used to assess the amplitudes of accommodation and convergence, the accommodative and convergence facility (the rate at which these parameters can be changed) is not normally assessed in the UK. This may be a more relevant measure of an individual's functional control of their accommodative and convergence mechanisms and of the ease with which these become fatigued; Hennesey et al. (1984) showed that children with asthenopia performed significantly worse at a test of accommodative facility. The literature shows that in the USA a "flipper" test is sometimes used to assess accommodative facility (Cooper 1987), which involves the patient fixating a near target and his stimulus to accommodate being varied from 1.50 D in front of the target to 1.50 D behind. After each change of the stimulus the patient reports as soon as the target becomes clear, when the stimulus is immediately changed again; the number of cycles that can be achieved in a given time is recorded. A similar test, using prisms, for vergence facility has been described (Griffin, 1982).

These tests assume that accommodation or vergence changes between 2 equidistant points, one in front and one behind the target. The units chosen to measure this distance can be a source of error. Griffin (1982), for example, inappropriately chose centimeters, resulting in an unequal stimulus to vergence that did not reflect the available vergence reserves. It has been claimed that binocular testing of accommodative facility reflects the interactive nature of the relation between accommodation and vergence (Siderov and DiGuglielmo, 1991). Such tests, however, exercise the unnatural action of altering accommodation without changing the vergence. This could explain why the results of these tests have been shown to correlate poorly with symptoms (Siderov and DiGuglielmo, 1991).

The author designed and experimented with a new test that simultaneously varied the stimuli to both accommodate and converge, and hence more closely represented normal binocular vision. Careful calculations and graphical solutions ensured that the theoretical design was appropriate; in particular, that the relationship between accommodative and vergence stimuli was correct. The final design consisted of a binocular twirl (flipper) with one pair of lenses of power -1.50 DS and 3.25 Δ base out each lens, and the other pair of power +1.50 DS and 3.25 Δ base in each lens. Although it was felt that this test should screen for defects of accommodative and/or vergence facility, it still seemed to imperfectly reflect the normal visual environment owing to the absence of a stimulus to proximal vergence and accommodation.

Hence, in the present study a more pragmatic test was used that measured the rate at which the subject could change his vergence and accommodation between distance (3 m) and near (30 cm) targets; this was abbreviated to the "D/N" test. It seems likely that performance at this test is affected by 4 main types of skills, including visual skills; these are numbered 1-4 in Figure 7.1. This figure also schematically illustrates several factors other than vergence and accommodation that constitute relevant "visual skills" and, in view of these, a control condition was included in which the subject only read from the near target. The success of this control condition in isolating the desired visual factors is also encoded in Fig. 7.1.

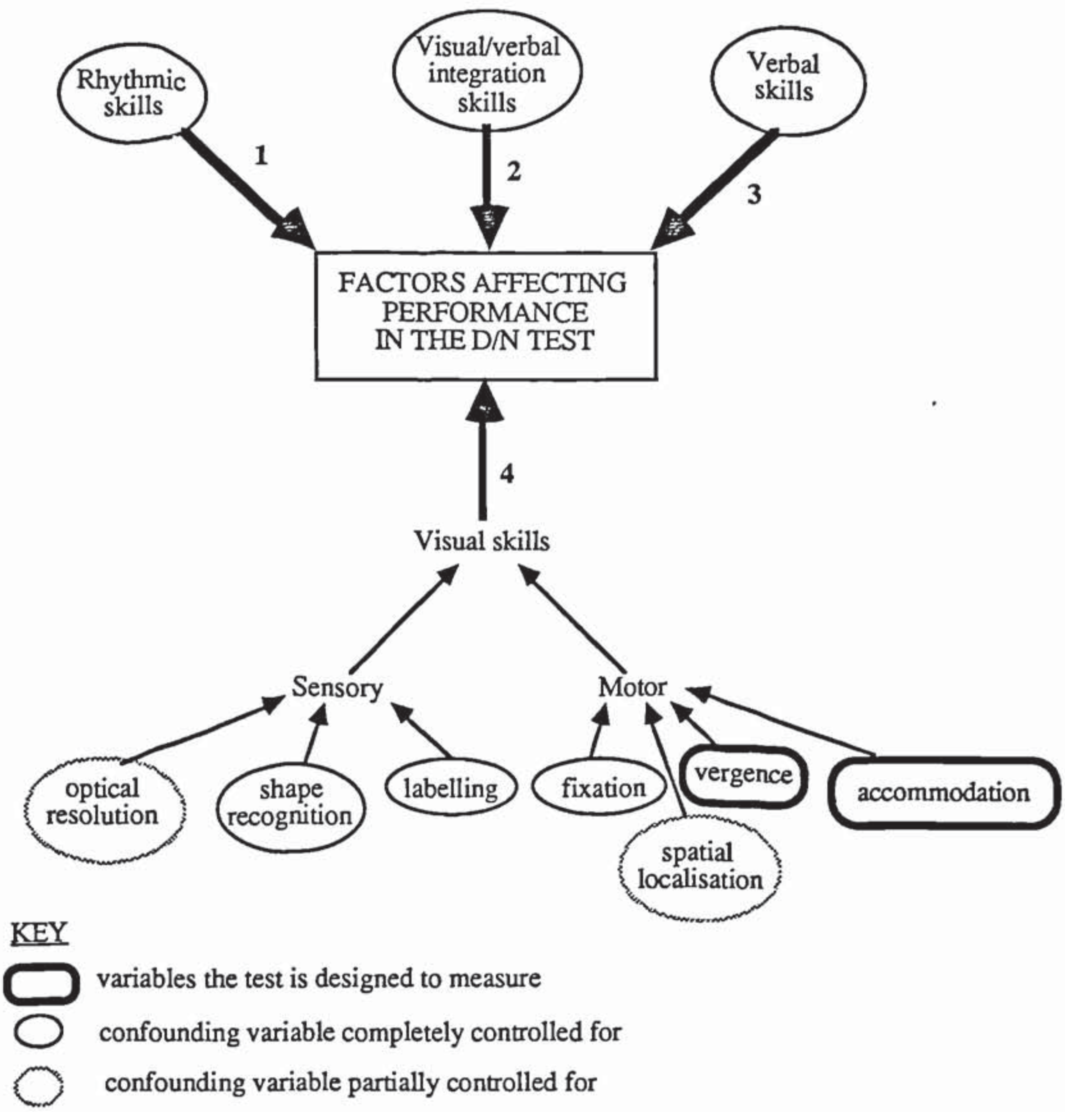

Figure 7.1 A schematic diagram illustrating the variables involved in the D/N test, and the success of the control (near target only) condition in controlling for these (see text). Spatial localisation is a factor that, although sensory in origin, is an essential precursor of precise motor function and has therefore been classified as a motor factor.

Procedure

The targets were reduced reproductions of the visual search task (*see* Figure 6.1) that, at the appropriate working distances, subtended 11.7° x 5.7°. The print size was equivalent to 6/9 (0.667) and the target was illuminated at 115 cdm^{-2}. Trials had shown that this type of target was particularly appropriate, since the size and proximity of the groups of numbers meant that these could only be read when the subject had cleared any blur or diplopia. Since 4 numbers can easily be assimilated in one fixation, the child had time to read one block each time before changing his fixation to the other target. The number of half cycles that could be completed in 90 seconds was recorded.

To minimise learning effects, 2 near targets (A and B) were used; these were of identical design, but comprised different numbers. The subject was instructed that he should start with the near target and read out the first four numbers (individually) and then the first 4 in the distance, then the next 4 at near, and so on. He was told not to read the numbers until they were completely clear and single, and that if he lost his place on a card he should read the number that he thought was nearest to the correct place without hesitating. After sufficient practice attempts with the near target A and the distance target, the near target was changed to B and the subject was started (commencing at near). The experimenter counted up the number of half cycles and noted those completed after 30, 60, and 90 seconds, and also observed the patient to ensure that the appropriate vergence movements were occurring. An alternative method of ensuring binocularity would be to have subjects report whether polarised letters faded (Siderov and DiGuglielmo, 1991); this was felt to be too subjective for use with the present population. The near target was then changed back to A and the subject was asked to read these numbers out alone (ignoring the distance target). The number of half cycles for these was recorded again at 30, 60, and 90 seconds.

7.4.6 Modified Dunlop Test

A modified Dunlop Test was carried out using the Mallett Unit in the same way as in the pilot study (*see* Section 6.2.9.2). To further control against false responses, the polarised filters were reversed in the order ABAABABBAB. Two types of additional information were recorded (although not for the first few subjects). In many subjects a fixation disparity was elicited on some trials without the introduction of extra prism and a note, therefore, was therefore made of the number of trials for which a prism *was* required to induce the fixation disparity. Secondly, in view of the controversy surrounding the reliability of this type of test (*see* Section 3.3), the quality of each subject's response was arbitrary graded by the examiner on a scale of 0 to 5, with 5 representing the best witness and 0 signifying refusal to participate.

7.4.7 Pattern Sensitivity

The procedure was similar to that of Wilkins et al. (1984, experiment 5), but included a control target in case the dyslexic children responded differently to the questions because of heightened suggestibility. This control target was of similar size and space-averaged luminance to the patterned target, but of a design that should not produce pattern glare. Wilkins et al. (1984, experiment 1) showed that subjects reported virtually no adverse effects from viewing a grating over approximately 20 cycles/°. They also showed (experiment 10) that pattern glare increased with increasing contrast up to 30% contrast, when the effect of increasing contrast became minimal.

The subjects therefore were shown 2 black and white gratings, both of which were circular targets, subtending 13.6° (diameter), mounted centrally on white card (subtending 45° x 35°). The subjects fixated a 1 mm central black spot and at the viewing distance of 30 cm the patterns had the following properties:
Grating A (experimental): 4.2 cycles/°, duty cycle 50%, contrast > 40%.
Grating B (control): 24 cycles/°, duty cycle 50%, contrast > 40%.

7.4.7.1 Procedure

The subjects were briefly shown the gratings and the procedure was described. They were then asked the first of the following questions and were shown each grating for approximately 10 seconds:

do you see a colour or colours?
do the lines appear to bend?
do the lines seem to blur?
does the pattern flicker?
do the lines wobble or shimmer?
do parts of the pattern disappear and reappear?
do you see any other patterns, shapes, or glare?

This procedure was repeated for the other questions; the order of presentation of the gratings was alternated according to an ABBA design, starting with the control grating. Additional information was obtained by asking a subject, when he saw an illusion, whether it was a "small amount of ..." or "a lot of ..." that anomalous effect. The illusion was thus scored as "mild", "moderate", or, if the subject experienced such discomfort that he attempted to avert his gaze, "severe". This method of scoring facilitated statistical analysis when a subject reported the same illusion with both gratings (*see* Section 8.3.6.1).

7.4.8 Investigations of Parallel Visual Processing

7.4.8.1 Spatial Contrast Sensitivity Function

Previous Research

Lovegrove et al. (1982) measured the spatial contrast sensitivity function for children with a specific reading disability (SRD) and children who read normally. These researchers used photographic prints of sine-wave gratings that gave a 4° circular field with space-averaged luminance of 10.3 cdm^{-2}. They tested at spatial frequencies of 2, 4, 8, and 12 cycles/°, and found that, compared with the controls, the SRD group had impaired contrast sensitivity at low spatial frequencies relative to that at high spatial frequencies. The most significant difference between their groups can be obtained by taking the ratio of the contrast sensitivity at 2 to 12 cycles/°. The oblique effect was found to be the same for the SRD and control groups.

Martin and Lovegrove (1984) found that, for field sizes between 2° and 8°, spatial summation was the same for SRD and control children. Changing luminance had a smaller effect on contrast sensitivity for high spatial frequencies in the SRD than the control group, and this effect was greatest at low luminance levels (3.42 cdm^{-2}) compared with high levels (102.74 cdm^{-2}).

Method in the Main Study

In the main study a commercially available contrast sensitivity system (Vistech VCTS Near Vision Test, Vistech Consultants Inc.) was used in such a way that the experimental conditions of Lovegrove et al. (1982) were replicated within the tolerances established by Martin & Lovegrove (1984). This test consists of photographic prints of sine wave gratings at 5 contrast levels for each of 5 spatial frequencies. In the main study the test was viewed at a distance of 30 cm where the diameter of the gratings subtended 2.5° and the spatial frequencies were 1, 2, 4, 8, and 12 cycles/°. The test was carried out binocularly and an incandescent light source was used to give a luminance of 10.3 cdm^{-2}.

Lovegrove and colleagues exposed each target individually for a fixed duration, whilst our targets were permanently present so that the subjects viewed each target in real time. The effect of stimulus duration (from 40 ms to 1000 ms) on the contrast sensitivity function has been investigated for 14 year old (Lovegrove et al., 1980a) and 12 year old (Lovegrove et al., 1982, experiment 1) SRDs and controls. Experimental and control groups performed similarly at short stimulus durations, but with longer durations (over about 80 ms) there was a difference in the pattern of sensitivity across spatial frequencies between the two groups. The normal fixation pause between saccades during the examination of any visual scene, including reading, is 200-400 ms (Yarbus, 1967). It has been suggested that, during saccades, the transient visual system inhibits the image that was formed by the sustained system during the preceding fixation (*see* Section 2.7.1.4 and that this prevents visual persistence during normal viewing. A similar inhibitory effect may occur at target offset in Lovegrove's experiments but, since similar gratings are known to have a visual persistence of up to 300 ms (Bowling et al., 1979), saccadic suppression would seem to have a greater effect than offset suppression. It seems likely that at least 3 saccades usually occurred during the 1000 ms duration of

Lovegrove et al. (1980a); hence, it seems appropriate to consider this as equivalent to real time (unlimited) viewing. The latter method also has the advantage of more closely resembling the normal viewing conditions during reading.

It is not clear whether the contrast step sizes in the present study differed from those in Lovegrove's experiments, since these were not given. In the normal clinical use of the Vistech Test only one plate is used, allowing a single estimate of contrast sensitivity at each spatial frequency. Kennedy and Dunlap (1990) assessed the reliability of this test and suggested that all 3 test plates should be used to detect subtle differences; this procedure was used in the main study. Lovegrove et al. (1982) had their subjects view the target monocularly. Pardhan et al. (1991) found that, although binocular V/A was equal to the best monocular V/A, the binocular contrast sensitivity showed summation and inhibition depending on the difference between the monocular performance. Hence, to more closely represent the normal reading situation, binocular viewing was used in the present study.

7.4.8.2 Temporal Contrast Threshold

Previous Research

Flicker thresholds are thought to be mediated by the transient system, or are at least by a separate flicker detecting system (Lovegrove et al., 1986a). Martin and Lovegrove (1987) assessed the flicker contrast sensitivity in SRDs and normal readers for targets of different spatial and temporal frequencies. For all conditions, the SRDs were less sensitive than the controls, and this difference increased with temporal frequency (from 5 to 25 Hz) and, to a lesser extent, with spatial frequency (1 to 12 cycles/°). This last finding, which is counter-intuitive (high spatial frequency detection is not thought to be mediated by the transient system), was explained by Martin and Lovegrove (1987) in terms of tonic mutual inhibition between the 2 systems.

Brannan and Williams (1988) investigated the effect of age and reading ability on flicker threshold. Their stimulus was a homogeneous field of light presented on a cathode ray tube with a P-31 (green) phosphor. This subtended 12.3° and was surrounded by a circular field that was matched in space-averaged luminance (50 cdm^{-2}). They varied flicker modulation depth for various temporal frequencies (4 to 24 Hz) and found that poor readers (aged 8 to 12 years) had significantly lower sensitivities than the controls; for most ages this difference was maximal at about 10 Hz. This finding was still present when good and poor readers who were matched for reading age were compared, indicating that the result was not caused by differences in reading skills. Burbeck (1981) however, criticised the use of the psychophysical method of adjustment in experiments investigating pattern and flicker thresholds using counterphase flickering gratings.

Merigan and Maunsell (1990) have examined the transient system function of monkeys whose magnocellular layers of the lateral geniculate body were lesioned. The post-lesion sensitivity to 1 cycle/° gratings, surprisingly, was unaffected, but they found a very severe reduction in the sensitivity to the 10 Hz flicker of a Gaussian blob.

Apparatus

The apparatus in the main study was designed to create a stimulus that would replicate the most significant findings of Brannan and Williams (1988) and one that, according to the findings of Merigan and Maunsell (1990), was exclusively related to magnocellular activity. The target was a homogeneous green field, subtending 12°, which flickered at 10 Hz and was surrounded by a circular green field of matched space-averaged luminance. The temporal contrast (modulation depth) was varied to obtain the threshold. For practical reasons, the apparatus needed to be compact and portable and a unit was designed that could be inserted into an optometric trial frame. The design, construction, and calibration of this apparatus is described in Appendix 2.

Psychophysical Considerations

Wetherill and Levitt (1965) reviewed several methods for the sequential estimation of points on a psychometric function, which can be described as the rule by which a subject's binary response is designated "positive" or "negative". The simplest of these is the "up and down" rule which detects the stimulus level at which the probability of a positive response is 50%. With this procedure, which is also called the Békésy or staircase method, the level of the test stimulus is varied in steps of a constant size, and trials are made sequentially. When a positive response is obtained the following observation is taken at the next lower level, and vice versa; any number of trials between 2 changes of response is called a run. The threshold is calculated by taking the mean of the final value in each run; if the response is plotted as a graph these points will be the peaks and valleys.

The staircase method should be started from the best estimate of the threshold (Cornsweet, 1962) and should be stopped after a given number of runs have been completed (Wetherill and Levitt, 1965). The step sizes should be the size of the differential threshold (Cornsweet, 1962). An improved technique was suggested by Wetherill and Levitt (1965) where the up and down rule is operated for at least 6 runs and an estimate is made of the threshold from this data; the sequence is then restarted from this estimate but with half the step size originally used. Advantages of the staircase method are that it requires the presentation of many fewer stimuli than any other psychophysical method (this is a particularly important consideration in studies involving children) and, compared with the method of adjustment, there is no ambiguity about what is actually happening (Cornsweet, 1962). Rose et al. (1970) used computer simulations to investigate the statistical properties of staircase estimates, which showed the up and down method to be better than the forced choice method.

Brannan and Williams (1988) used a simple up and down staircase method; a similar technique was used in the present study. Two sets of at least 12 runs were carried out, the first using fairly coarse step sizes to determine the approximate threshold; this was then used as the starting point for the second run with finer step sizes. The initial starting point was determined after trials on young adults and dyslexic children who had been seen as case studies.

Procedure

The room lights were dimmed so that their effect, relative to the target illumination, was irrelevant and the subject was adapted to this level for approximately 4 minutes. The pulse duration was set at 2 seconds and the flicker frequency was set and maintained at 10 Hz ± 0.2 Hz throughout the experiment. The left cell of the trial frame was occluded and the right cell was exactly centred on the visual axis of the right eye using a clear lens with "cross wires" drawn on it; the flicker eyepiece unit was then inserted in the right cell. During the experiment each pulse was preceded by a verbal warning. The subject's attention was drawn to the centre of the field; this was slightly dimmer than the surround, although the border was ill-defined. The flicker modulation depth was adjusted to the minimum setting (so that flickering would not be perceived), the subject was told that an "extra, but dim light" would come in the centre for 2 seconds, and the pulse was triggered. This was repeated until the subject could clearly see the pulse, and he was told that on the next few trials the pulse would be flickering. The modulation depth was adjusted to the maximum setting (approximately 0.04 contrast) and the pulse was repeatedly triggered until the subject could reliably detect the flickering.

The subject was told that the flickering would only be present on some of the trials, and he had to detect its presence. Several practice trials followed (at least 10, but more when necessary) during which the modulation (contrast) was gradually reduced to approximately 0.003, but interspersed with trials when the flicker was imperceptible. The subject was told that the experiment would now start, and it was explained that each time there would be a random probability of the stimulus flickering or not. The starting point was 0.0025 modulation. A step size of 1.26×10^{-4} was used for the first series of runs, and the results were plotted on a graph as the experiment proceeded. When the graph had approximated a plateau for at least 12 runs the trial frame was removed for a rest period. The approximate threshold was estimated from the first series, and the patient was re-instructed as before. A second series of runs was commenced, but with a step size of 0.6×10^{-4}. The average threshold was calculated from the final 6 peaks and 6 troughs of the second series of runs.

7.4.9 Visual Search Task

7.4.9.1 Apparatus

Minor modifications were made to the visual search task that was used in the pilot study (*see* Section 6.2.11). The non-search numbers (those that the subject was not asked to count) were adjusted so that there was, as far as possible, an equal number of every numeral in each sub-test. Cornelissen (1990) and Cornelissen et al. (1991) suggested that reading errors that resulted from visual problems were best detected using a small print size; hence the test sheets were laser printed in 10 point Helvetica, instead of the 12 point used in the pilot study. The final test sheets are shown in Appendix 3.

Wilkins and Nimmo-Smith (1987) gave formulae for the derivation of the spatial properties of text. The angular height of the page was calculated as

$$2\tan^{-1}(h/2d)$$

and the angular width similarly. The fundamental spatial frequency of the text was calculated as

$$1/\tan^{-1}(s/d)$$

and the duty cycle was estimated as

$$(s-x)/s.100\%$$

where

h = distance from the top of the text to the bottom
w= distance from left to right extremity of the text
s = distance between the bottom of one line and the bottom of the line above
d = viewing distance, and
x = height of the central body of the letters (ignoring ascenders and descenders)

The above formulae were used to calculate the spatial properties of the main study VST sub-tests, and these are given in Table 7.2. One potential source of error with these calculations, that they ignore the effect of letter ascenders and descenders (Wilkins and Nimmo-Smith,1987), was avoided by using numbers. However, the variable viewing distance (*see* Section 6.2.11.1) was a source of error in the present study.

sub-test	page height	page width	SF	duty cycle
3	30.0	27.5	0.19	89.1
4	21.1	27.9	0.19	88.9
5	16.0	28.2	0.19	77.8
R	4.0	20.4	0.58	66.7

Table 7.2 Spatial properties of visual search task sub-tests. Measurements of page height and width are in degrees, spatial frequencies ("SF") are in cycles per degree, and duty cycle is in percentages.

The parameters in Table 7.2 do not take account of the low print density in sub-tests 3-5. Of these, sub-test 5 had the highest print density per line, yet approximately 60% of the line was taken up by spaces between the blocks of characters. By design, sub-test R resembled normal print and only 30% of the line was taken up by the spaces between "pseudo-words". Hence, only sub-test R possessed the spatial properties that Wilkins and Nimmo-Smith (1987) found in printed text and that they suggested could induce pattern glare. Unfortunately, the small vertical dimension of sub-test R (*see* Table 7.2) would reduce the likelihood of it triggering pattern glare. This could have been overcome by placing lines of text above and below the search material (Evans et al., 1991), although in the present study it was felt that this might have distracted and confused some of the children.

7.4.9.2 . Procedure

The procedure was similar to that in the pilot study (*see* Section 6.2.11.2) except for the order in which the sub-tests were performed. In the main study the binocular and monocular conditions were interwoven in an ABBA design, which was consistently used for all subjects. The test commenced with sub-test "3" binocularly, and proceeded through sub-tests "4" monocularly, "5" monocularly, "R" binocularly; then "2" monocularly, "3" binocularly, "4" binocularly, and "R" monocularly. This order was designed to control for practice effects and to avoid the subjects learning the correct response.

If a subject made excessive errors (more than 2 in an individual search, or more than 3 in any subtest) or took more than twice as long on one individual search than on the others in that subtest, that particular search was repeated after the others in the sub-test. A maximum of 2 attempts was allowed for each search, and the best measure of accuracy and mean measure of time taken were used for the data analysis. If subjects were performing poorly they were encouraged to concentrate harder, but such encouragement was only given after an even number of sub-tests.

7.4.10 Symptoms and History

7.4.10.1 Procedure

Similar questions were asked as in the pilot study (*see* Section 6.2.4). Subjects were not asked any questions about their schoolwork, the psychological assessment, or any details of a learning difficulty, and these subjects were positively avoided if brought up by the child or parents. Inevitably, in some cases it became apparent during the examination whether the child was from the dyslexic or control group. Where the blind protocol was broken, this was noted on the record card.

Data Collection and Quantification

Several problems were involved in the analysis of symptomatology. Firstly, patients reports are often vague, and this tendency was probably exaggerated for children where parents are often the source of information. Secondly, the data had to be transformed into a type suitable for analysis and the process of translating qualitative statements into quanitative values may result in a loss of information. Thirdly, the parents of the dyslexic children had all approached a psychologist for assessment of their child's learning difficulties, whereas the control children had not. It is possible, therefore, that the dyslexic group contained some individuals whose parents were more likely to notice abnormalities in their children.

The main questions that were asked are summarised in Table 7.3; it is stressed that the actual questions were more comprehensible, lengthier, synonyms of those in the table. For example, the difference between an eye examination and a school sight test was explained and the occurrence of headaches due to a feverish illness was differentiated from the presence of nausea secondary to a headache.

The "close family" was defined as the child's parents or siblings. A "binocular vision problem" was explained as a turning eye, eye muscle operation, or need for eye exercises; reports of a "lazy eye" or of occlusion therapy were only considered to be evidence of a binocular vision problem when associated with measurable amblyopia that could not be attributed to anisometropia. Glasses were considered to be only worn rarely when they were not normally worn in class. The phrase "double vision" was explained and if necessary demonstrated, and reports of physiological diplopia were identified and excluded. Most children who, upon questioning, complained of diplopia had not previously reported this to their parents, and details tended to be vague. Only the presence or absence of episodes of diplopia, with glasses if worn, during the last 6 months were therefore recorded. If a child normally wore glasses in class, the questions about clarity of vision were related to when the glasses were worn.

question	answer
Have you ever had an eye examination before?	no=0 yes=1
Have you ever worn glasses?	no=0 yes=1
Do you wear glasses at the moment for distance/near/both/rarely?	distance/near/both/rarely
Have you ever had an eye disease or operation?	no=0 yes=1
Have you ever had a binocular vision problem?	no=0 yes=1
Is your distance vision normally clear or blurred?	clear=0 blurred=1
Does your distance vision ever go blurred, if so, how frequently?	never blurred=0 ≤once weekly=1 ≤once daily=2 ≤4x daily=3 ≤every 2hrs=4 ≥every hr.=5
If your distance vision does blur, how long for?	never blurred = 0 ≤ 5 secs. = 1 ≤ 1 min. = 2 ≤ 5 min. =3 ≤ 10min. = 4 > 10 min.=5
Is your near vision normally clear or blurred?	clear=0 blurred=1
Does your near vision ever go blurred, if so, how frequently?	never blurred=0 ≤once weekly=1 ≤once daily=2 ≤4x daily=3 ≤every 2hrs=4 ≥every hr.=5
If your near vision does blur, how long for?	never blurred=0 ≤ 5 secs. = 1 ≤ 1 min. = 2 ≤ 5 min. =3 ≤ 10min. = 4 > 10 min.=5
Do you ever experience double vision?	no=0 yes=1
Have you ever suffered, for a period greater than 3 months, from headaches that have been diagnosed as migraine?	no=0 yes=1
Do you suffer from headaches, including migraine (apart from when ill)?	no=0 yes=1
How often do you suffer from these headaches?	never or only when ill = 0 ≤ monthly = 1 ≤ fortnightly=2 ≤ weekly = 3 ≤ 2x weekly=4 > 2x weekly=5
When you get these headaches, are they associated with reading?	never = 0 sometimes = 1 always when reading = 2
Is your general health good?	yes=0 no=1 (+ details)
Are you taking any medication?	no=0 yes=1 (+ details)
Do you suffer from any allergies (including hay fever)?	no=0 only >1 year ago=1 now, or within 1year=2
Has anyone in your close family ever had a binocular vision problem?	no=0 yes=1
Has anyone in your close family ever had recurrent headaches which have been diagnosed as migraine?	no=0 yes=1
Has anyone in your family ever had epilepsy?	no=0 distant family=1 close family=2

Table 7.3 Summary of questions asked in main study symptoms and history section, and "rules" for scoring the answers. The questions in the table are precis of the actual questions that were asked; the latter varied according to the level required for satisfactory communication with parent/child. *See* text for more details.

The diagnosis of migraine is complicated (Clough, 1989a; Diamond and Medina, 1980) and the details of headaches proffered by the children or parents were inadequate for diagnosis by the author. Hence, only a medical diagnosis of migraine was taken as evidence of this condition; if a general medical practitioner was said to have suggested that headaches "might be migraine" this was not considered to be a diagnosis. Most of the 5 million people in the UK who suffer from migraine do not consult their doctor about it (Clough, 1989b); hence, the present study is likely to provide an extremely conservative estimate of the incidence of migraine. Headaches were considered to be "associated with reading" when they were more likely to occur during or immediately following reading than at other times; a vague description of headaches after school did not meet this criterion. An equivocal history of allergy (e.g., eyes water in summer, thought to be mild hay fever but not diagnosed) was scored as "1".

CHAPTER 8

MAIN STUDY:

RESULTS AND ANALYSES

8.1 INTRODUCTION

8.1.1 Subjects and Raw Data

The final dyslexic group comprised 39 children, 30 of whom were male (77%). A total of 240 children were screened as potential controls, 59 of whom had suitable psychometric profiles and attended for the optometric examination. Forty-three of these were selected, using only the psychometric data, for the final control group; 33 (77%) of these were male.

The raw data for the main study results are given in Appendix 3 and the reference numbers allocated there to each subject are be used throughout this chapter. The prefix associated with each number identifies which group the subject belongs to: "d" for dyslexic, and "a" or "b" for control (these 2 alternatives differentiate the school that the control attended).

8.1.2 Introduction to Statistical Analyses

Where an assessment of the frequency distribution of data suggested that they may not be normally distributed they were subjected to a test of normality. The test that was used employed the Kolmogorov-Smirnov test to compare the samples with a theoretical normal distribution. This was applied to the complete subject sample (control and dyslexic groups combined), and a p-value less than 0.05 indicated that the data did not come from a normal distribution. Parametric and non-parametric statistics were then used as appropriate. Where there was a non-significant tendency for the data to differ from a normal distribution then both parametric and, wherever possible, non-parametric analyses were used.

When correlation co-efficients were required these were calculated for the control and dyslexic groups individually, and for the sample as a whole, when both groups were combined. The difference between the Pearson correlation co-efficients for the dyslexic and control groups, when appropriate, were compared statistically. When Spearman correlation co-efficients were used, an analogous comparison was not possible since the significance of the difference between 2 Spearman co-efficients cannot reasonably be assessed (Francois, 1991).

The level of significance required to support a hypothesis was taken as $p \leq 0.05$; the finding was noted as a non-significant tendency when $0.05 < p < 0.10$. Where an optometric variable was investigated at which dyslexic children, in previous studies, had been shown, invariably, to have infra-normal performance, one-tailed probability values were calculated. In all other cases, 2-tailed values were used.

8.2 PSYCHOMETRIC DATA

The descriptive statistics for the main variables from the psychometric data are listed in Table 8.1 and are illustrated in Figure 8.1. It should be noted that the dyslexic group was selected using a regression equation involving the Neale reading test result and performance IQ; *see* Section 7.2.2.1.

variable	group	mean	SD	min.	max.
age	control	118.3	15.4	89	140
	dyslexic	119.9	16.1	90	147
IQ	control	111.2	11.1	88	135
	dyslexic	110.8	11.3	87	135
reading age	control	136.9	13.7	104	150
	dyslexic	96.3	12.8	72	121
spelling age	control	147.1	23.8	100	192
	dyslexic	90.4	15.0	69	135

Table 8.1 Summary of descriptive statistics of main study psychometric data. "IQ" is performance IQ (WISC-R or RPM) in deviation IQ points, all ages are in months, and the reading and spelling ages are derived from the Schonell and Vernon test results respectively. "SD" is standard deviation, and "min." and "max." minimum and maximum results respectively.

A normality test indicated that the data in Figure 8.1 were normally distributed and, when the relationships were tested statistically, there were no significant differences between the 2 groups in terms of chronological age ($p > 0.7$; unpaired t-test, 2-tailed) and performance IQ ($p > 0.3$; unpaired t-test, 2-tailed), but there were highly significant differences between the groups' reading ages ($p \leq 0.0001$; unpaired t-test, 2-tailed) and spelling ages ($p \leq 0.0001$, unpaired t-test, 2-tailed):

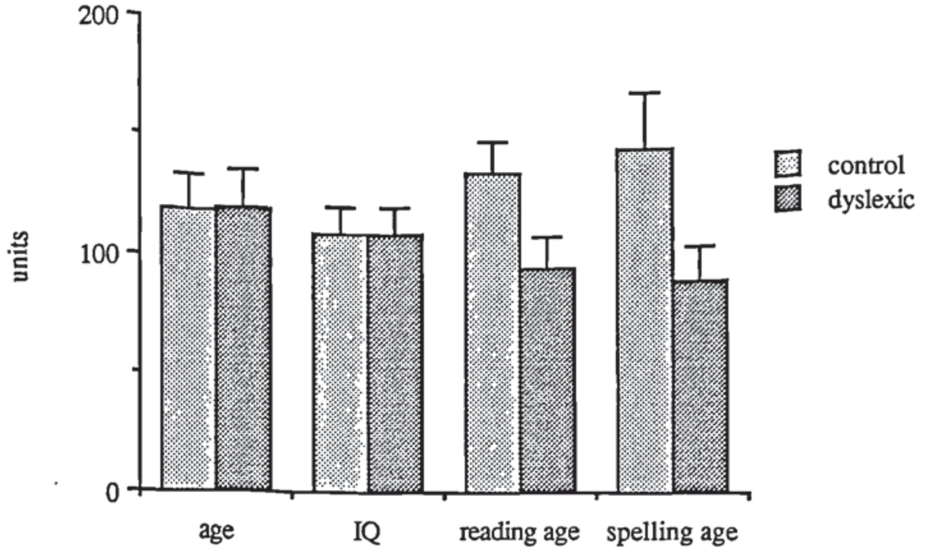

Figure 8.1 Graphical comparison of key psychometric data for the control and dyslexic groups. The units are ages in months or deviation IQ points, and "IQ" is from the performance WISC(R) or RPM tests, and "reading age" and "spelling age" are calculated from the Schonell and Vernon graded word tests respectively. The error bars represent 1 standard deviation.

8.3 OPTOMETRIC DATA

8.3.1 Ophthalmoscopy and Ocular Motility

No ocular pathology was detected. Two subjects (d07 and b22) had diffuse or absent foveal reflexes; this finding can be physiologically normal. Three subjects (d03, d10, and d19) had slow or reduced pupil reflexes. The ocular motility test did not detect any incomitancy, although a lack of smoothness of pursuit eye movements was noted in 5 members of the dyslexic group (d03, d07, d14, d16, and d19). This has been found before (*see* Section 2.5.3) and has been described as choreiform or cogwheel eye movements, or saccadation of pursuit. These findings, without objective eye movement analysis, represent an "anecdotal" qualitative observation.

8.3.2 Basic Refractive Tests

These data were successfully collected on all subjects. The results for the parameters in the analyses below were found to differ significantly from a normal distribution ($p < 0.05$, except for the difference between the right and left eyes' near V/A where $p < 0.10$); non-parametric tests, therefore, were used throughout.

8.3.2.1 Visual Acuities (V/A)

The results were recorded as Snellen fractions and were converted to the log of the minimum angle of resolution ("logMAR" units). This scale places the normal level of V/A (6/6) at 0.00, with increasingly positive numbers reflecting worsening, and increasingly negative numbers improving, V/A. The near vision chart was specifically designed for logMAR measurement, but the distance chart was a conventional Snellen Chart so that the calculation of the logMAR values involved interpolations and minor approximations.

The descriptive and comparative statistics in Table 8.2 support the hypothesis that the dyslexic group had worse near binocular V/A, and also suggest that they have significantly worse distance binocular V/As. The inter-ocular difference was not significantly different in the 2 groups. A ceiling effect was apparent, even for the near logMAR chart.

variable	group	N	median	min.	max.	p
binocular distance V/A	control	43	-0.08	0.48	-0.10	0.0164
	dyslexic	39	-0.06	0.22	-0.10	
binocular near V/A	control	43	-0.06	0.24	-0.10	0.0018
	dyslexic	39	0.00	0.50	-0.10	
near V/A inter-ocular difference	control	43	0.06	0	0.30	0.58
	dyslexic	39	0.04	0	0.68	

Table 8.2 Descriptive and comparative statistics for V/As (in logMAR units). "N" is total number, "min." is minimum, and "max." is maximum (N.B. the minimum, more negative, values represent better V/As). The "p" values in the right hand column were calculated using the Mann-Whitney U test (2-tailed, corrected for ties).

The difference between the best monocular V/A and the binocular V/A at distance was calculated, and this was not significantly different between the 2 groups (p = 0.66; Mann-Whitney U test, 2-tailed, corrected for ties). Similarly, the difference between the best monocular V/A and the binocular V/A at near was not significantly different in the 2 groups (p = 0.52; Mann-Whitney U test, 2-tailed, corrected for ties).

8.3.2.2 Retinoscopy

A systematic error can occur during retinoscopy owing to a different working distance for each eye; hence, the SER for each eye was analysed separately. For non-infants of normal intelligence subjective refraction is normally more reliable than the objective method of retinoscopy (Borish, 1975; p. 771), although one exception to this can be cases of latent hypermetropia. The retinoscopy SERs of the 2 groups were compared (*see* Table 8.3), and the hypothesis that the dyslexic group would have increased hypermetropia relative to the controls was not supported.

variable	group	N	median	min.	max.	p
right eye mean SER	control	43	+0.88	-4.50	+5.00	0.44
	dyslexic	39	+0.75	-1.50	+7.25	
left eye mean SER	control	43	+0.75	-4.00	+6.38	0.96
	dyslexic	39	+0.75	-1.50	+9.00	

Table 8.3 Descriptive and comparative statistics for the mean SER (in dioptres) of each eye, as measured by retinoscopy. "N" is total number, "min." is minimum, and "max." is maximum. The "p" values in the right hand column were calculated using the Mann-Whitney U test (2-tailed, corrected for ties).

8.3.2.3 Subjective refraction and visual acuities

The mean SER for each subject was calculated from the data for the right and left eyes and the mean cylindrical correction for each subject was derived in a similar way. Ray and O'Day (1985) demonstrated that this is an appropriate method of analysing multi-eye data (pooling the right and left eye data from individual subjects can lead to high levels of significance being spuriously achieved). The anisometropia was calculated from the difference between the SER's of the right and left eye. The poorer presenting V/A in the dyslexic group was investigated by calculating the mean (for right and left eyes) corrected distance V/As. The descriptive and comparative statistics for these data are given in Table 8.4 and the frequency distributions of the mean SER results for the 2 groups are given in Figure 8.2.

variable	group	N	median	min.	max.	p
mean SER	control	43	+0.38	-4.00	+4.94	0.58
	dyslexic	39	+0.32	-1.75	+7.38	
mean cylinder	control	43	0.13	0	1.00	0.74
	dyslexic	39	0.13	0	1.25	
mean corrected V/A	control	43	-0.08	-0.10	0.40	0.008
	dyslexic	39	-0.04	-0.10	0.35	

Table 8.4 Descriptive and comparative statistics for subjective refractive error (in dioptres) and resulting distance V/As (in logMAR units). "N" is total number, "min." is minimum, and "max." is maximum (N.B. for V/As, the minimum, more negative, values represent better V/As). All cylindrical components were measured and recorded in negative cylinder form. The "p" values in the right hand column were calculated using the Mann-Whitney U test (2-tailed, corrected for ties).

Table 8.4 and Figure 8.2 do not support the hypothesis that there would be increased hypermetropia in the dyslexic group. Table 8.4 also shows that the astigmatic refractive error is similar in the 2 groups, but that the mean corrected V/A is significantly worse in the dyslexic group.

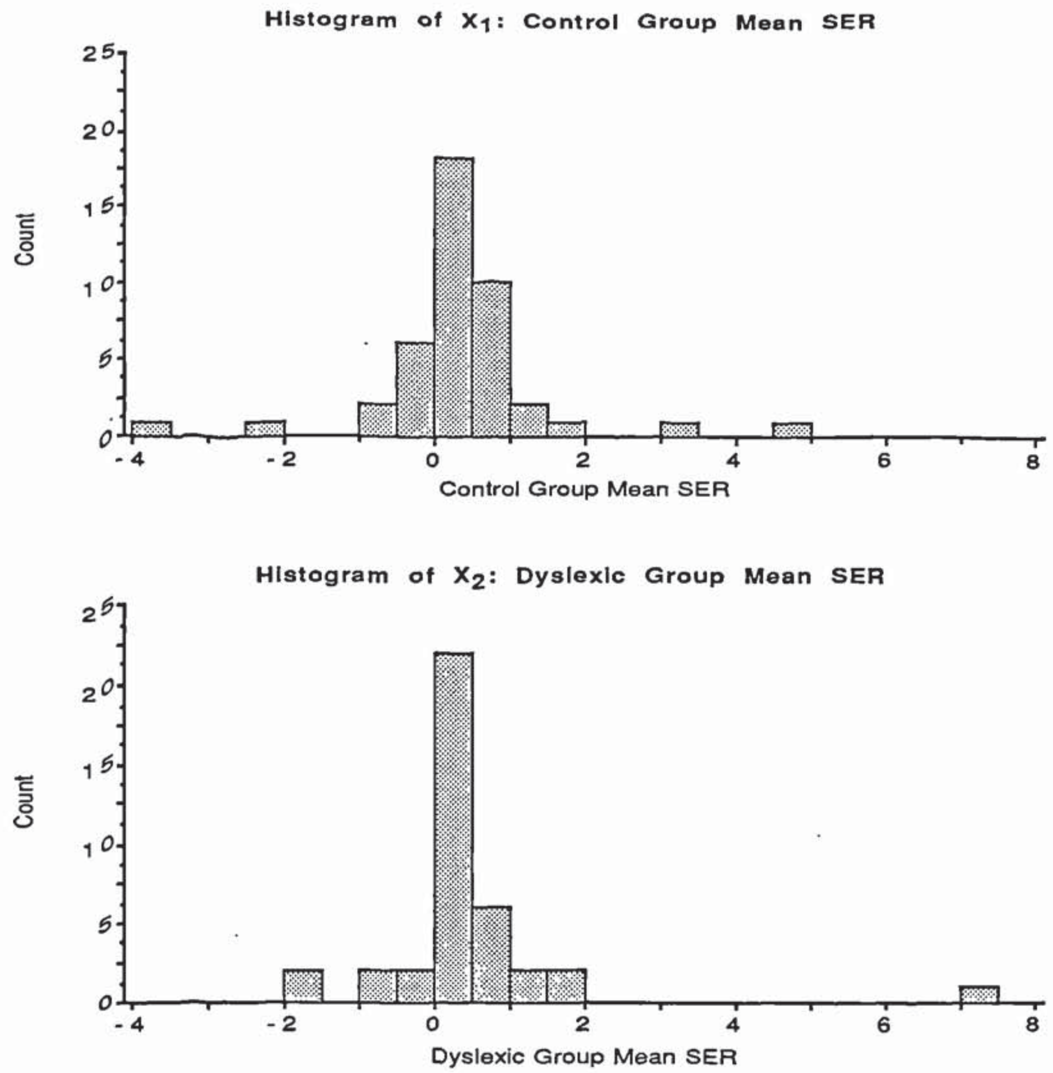

Figure 8.2 Frequency distributions for mean SER (in dioptres) for the control and dyslexic groups.

8.3.2.4 Summary and Discussion

There were no significant differences between the refractive errors of the 2 groups. It was mentioned in Section 2.3.3 that hypermetropia may be associated with low IQ, and this may account for some of the studies that found an association between increased hypermetropia and reading disabilities.

The present study did show a significantly lower level of distance V/A in the dyslexic group, and a highly significant worse near V/A; these findings do not appear to result from refractive errors. It is possible that these results are an artifact owing to the dyslexic group confusing the identity of the letters because of high level linguistic (decoding) difficulties. However, this seems unlikely and was not apparent during the testing. These findings will be further investigated in Sections 8.3.3.9 and 8.3.4.1.

8.3.3 Binocular Vision and Orthoptic Tests

8.3.3.1 Cover Test

Distance

With the exception of one strabismic child (d03), all the subjects were orthophoric at distance by cover testing. The magnitude of the squint at distance in subject d03 was estimated to be 10 Δ right esotropia associated with 2 Δ right hypertropia.

Near

Excluding the strabismic subject, no heterotropias or hyperphorias were detected. The magnitude of the squint at near in subject d03 was estimated to be 15 Δ right esotropia associated with 2 Δ right hypertropia. A test of normality confirmed that the horizontal heterophoria by cover testing was not normally distributed ($p = 0.001$), and the appropriate descriptive statistics are given in Table 8.5. Comparative statistics did not support the hypothesis that the dyslexic group would have increased exophoria at near ($p = 0.36$; Mann-Whitney U test, 2-tailed, corrected for ties).

group	N	median	min.	max.
control	43	0	-2.0	+8.0
dyslexic	38	0	-3.0	+4.0

Table 8.5 Descriptive statistics for near cover test horizontal heterophoria (in Δ). "N" is total number, "min." is minimum, and "max." is maximum. All exophorias were entered as positive and all esophorias as negative values.

8.3.3.2 Dissociation Tests

Distance

A few of the results from this section were missing; this occurred when the subject suppressed the line target (the strabismic subject (d03) was in this category). The descriptive statistics for the vertical heterophorias are given in Table 8.6. The distribution of the data was skewed (most subjects had no vertical heterophoria), and there was a relatively small range of measurements with a step size of 0.5 Δ. A test of normality confirmed that the data were significantly different from a normal distribution ($p = 0.001$) and, therefore, non-parametric comparative statistics were used. The hypothesis that there would be an increased incidence of heterophoria in the dyslexic group was not supported (Mann-Whitney U test, 2-tailed, corrected for ties; $p = 0.198$).

group	N	median	min.	max.
control	42	0	0	+1.0
dyslexic	36	0	0	+5.0

Table 8.6 Descriptive statistics for the vertical heterophoria (in Δ), measured by the distance dissociation test. "N" is total number, "min." is minimum, and "max." is maximum. All hyperphorias were recorded as positive.

The horizontal heterophoria data were investigated in 2 ways. Firstly, the relative incidence of exophoria and esophoria was analysed in the 2 groups by assigning a positive value to the exophoric measurements and a negative value to esophoric measurements. Secondly, the magnitude of heterophoria (irrespective of the direction of the deviation) was investigated by converting these measurements to absolute values. The descriptive statistics for these are given in Table 8.7; a normality test showed that these data were normally distributed. Although Letourneau and Giroux (1991) concluded that the dissociated heterophoria was not normally distributed, their study suffered from several weaknesses, including major measurement artifacts. The authors gave insufficient data for their results to be re-analysed, although graphical inspection would suggest that their conclusions were invalid.

analysis	group	N	mean	SD	min.	max.
+ exophoria	control	42	-2.1	2.2	-8.5	+1.5
- esophoria	dyslexic	36	-1.4	1.8	-6.5	+2.0
absolute	control	42	2.2	2.1	0	8.5
values	dyslexic	36	1.7	1.5	0	6.5

Table 8.7 Descriptive statistics for the horizontal heterophoria (in Δ), measured by the distance dissociation test. "N" is total number, "SD" is standard deviation, "min." is minimum, and "max." is maximum. The "analysis" column in explained in the text.

There was no significant difference between the 2 groups in the absolute amount of horizontal heterophoria with this test (unpaired t-test, 2-tailed). Similarly, the hypothesis that the dyslexic group would exhibit more esophoria at distance was not supported, and in fact the controls tended to be more esophoric (unpaired t-test, 2-tailed; $p = 0.15$)

Near

The only data that were missing from this section were those of the strabismic subject (d03). In view of the relatively small range, the measurement step size of 0.5 Δ, and the fact that only one control had any hyperphoria, non-parametric statistics were used to analyse the vertical heterophorias. The descriptive statistics for this variable are given in Table 8.8. The hypothesis that there would be an increased incidence of heterophoria in the dyslexic group was not supported, although the trend was in this direction (Mann-Whitney U test, 2-tailed, corrected for ties; $p = 0.124$).

group	N	median	min.	max.
control	43	0	0	0.5
dyslexic	38	0	0	4.0

Table 8.8 Descriptive statistics for the vertical heterophoria (in Δ), measured with the near dissociation test. "N" is total number, "min." is minimum, and "max." is maximum. All hyperphorias were recorded as positive.

The horizontal near results from this test, like the distance results, were investigated in 2 ways: the relative incidence of exophoria and esophoria and the absolute magnitude of heterophoria, irrespective of the direction of the deviation. The absolute values were not normally distributed ($p = 0.018$) and the appropriate descriptive statistics are given in Table 8.9.

analysis	group	N	centre	SD	min.	max.
+ exophoria	control	43	-0.05	2.2	-9.0	+6.0
- esophoria	dyslexic	38	+0.16	2.2	-5.0	+6.0
absolute	control	43	1.0*		0	9.0
values	dyslexic	38	1.0*		0	6.0

Table 8.9 Descriptive statistics for the horizontal heterophoria (in Δ), measured with the distance dissociation test. "N" is total number, "centre" is the measure of central tendency (mean except for * when median), "SD" is standard deviation, "min." is minimum, and "max." is maximum. The "analysis" column is explained in the text.

There was no significant difference between the absolute amount of horizontal heterophoria with this test in the 2 groups (Mann-Whitney U test, 2-tailed, corrected for ties; $p = 0.42$). Similarly, the hypothesis that the dyslexic group would exhibit more exophoria at near was not supported (unpaired t-test, 2-tailed; $p = 0.68$).

The hypothesis that the dyslexic group would exhibit relatively more esophoria at distance and exophoria at near was further investigated by calculating the (prism) dioptric distance between the dissociated resting position of the eyes (passive position) at distance and near. This involved subtracting the near from the distance horizontal heterophoria. A more negative value, which may result from an esophoria at distance and an exophoria at near, could indicate a reduced tendency to diverge and converge the eyes away from the natural resting point of the vergence system, which is situated at about 1 metre from the observer (Owens and Leibowitz, 1983, pp. 30-37). The descriptive statistics for this variable are given in Table 8.10. The hypothesis that the dyslexic group would exhibit relatively more esophoria at distance and exophoria at near was not supported (unpaired t-test, 2-tailed; $p = 0.40$).

group	N	mean	SD	min.	max.
control	42	1.96	2.14	-2.5	+9.0
dyslexic	36	1.54	2.20	-2.5	+6.5

Table 8.10 Descriptive statistics for the difference between the distance and near horizontal heterophorias, in Δ. "N" is total number, "SD" is standard deviation, "min." is minimum, and "max." is maximum. A positive value indicates a relative exophoria at distance or esophoria at near.

The final hypothesis to be investigated in this section concerned the stability of response in the Maddox Wing Test (*see* Section 7.4.4.2). The data for this variable were integers from 0 to 2 Δ and many subjects scored 0. The frequency distribution, therefore, was skewed, and a normality test indicated that this significantly differed from a normal distribution (p = 0.005). Non-parametric analyses were therefore employed, and the descriptive statistics are given in Table 8.11. The hypothesis that the dyslexic group would exhibit significantly more horizontal vergence instability when the eyes were dissociated with this test was supported (Mann-Whitney U test, 2-tailed, corrected for ties; p = 0.046).

group	N	median	min.	max.
control	43	0	0	2.0
dyslexic	38	0.75	0	5.0

Table 8.11 Descriptive statistics for the stability of response in the Maddox wing test (horizontal reading), in Δ. "N" is total number, "min." is minimum, and "max." is maximum.

8.3.3.3 Near Associated Heterophoria

Subject d03 permanently suppressed the target in his strabismic eye and one other dyslexic subject also suppressed one eye in the horizontal assessment; full results for all other subjects were obtained. The hypotheses concerning the type and magnitude of the near associated heterophoria (measured with the Mallett Unit) were analogous to those for the near dissociated heterophoria.

Only the absolute values of the vertical results were analysed and the horizontal results were first analysed for type and magnitude of heterophoria (exophorias as positive numbers and esophorias as negatives) and then for absolute magnitude only. The latter variable did not approximate a normal distribution (p = 0.003); all other data in this section were normally distributed. The descriptive and comparative statistics are summarised in Table 8.12; the associated heterophoria was similar in the 2 groups.

variable	group	N	centre	SD	min.	max.	p
vertical	control	43	0.08	0.19	0	0.75	0.42
(absolute)	dyslexic	38	0.12	0.27	0	1.00	
horizontal	control	43	+0.20	0.91	-2.0	+3.0	0.36
+ exo/-eso	dyslexic	37	+0.03	0.71	-3.0	+1.0	
horizontal	control	43	0*		0	3.0	0.64*
(absolute)	dyslexic	37	0*		0	3.0	

Table 8.12 Descriptive and comparative statistics for near associated heterophoria (in Δ). "N" is total number, "centre" is the measure of central tendency (mean except for * when median), "SD" is standard deviation, "min." is minimum, and "max." is maximum. The "variable" column is explained in the text. The comparative statistics that were used to arrive at the "p" value in the right hand column were the unpaired t-test (2-tailed) or, when *, the Mann-Whitney U test (2-tailed, corrected for ties).

The stability of the response with the near Mallett Unit was assessed in 2 ways. The "sensory stability" was determined from whether both nonius strips were present constantly, or whether one or both faded or flickered. "Motor stability" was assessed by the dynamic stability of the strips; movement of one or both strip(s) represented a motor instability. Although several grades of each type of instability were recorded, it was felt that such grading was too subjective and the results, therefore, were transformed to a simple binary nominal scale of 0 for a completely stable response and 1 for an unstable response.

variable	group	N	median	min.	max.	p
sensory	control	43	1	0	1	0.64
instability	dyslexic	39	0	0	1	
motor	control	43	0	0	1	0.86
instability	dyslexic	37	0	0	1	
combined	control	43	1	0	2	0.71
instability	dyslexic	39	1	0	2	

Table 8.13 Descriptive and comparative statistics for stability of response on Mallett Near Unit. "N" is total number, "min." is minimum, and "max." is maximum. The "variable" column and scoring system are explained in the text. The comparative statistic which was used to arrive at the "p" value in the right hand column was the Chi-square test with continuity correction.

The sensory and motor stability results were also summed to permit an analysis of the incidence of combined motor and sensory instability. The descriptive and comparative statistics for these variables are given in Table 8.13; there were no significant differences between the 2 groups.

8.3.3.4 Near Point of Convergence

The only data missing from this section were for the strabismic subject (d03); all other subjects were able to report a clear subjective break point. The inter-pupillary distance was not measured. The data, therefore, were linearised by conversion to prism dioptres, using a similar method to that in the pilot study (*see* Section 6.3.2.3), except the value for the mean interpupillary distance of the age group in the main study was taken as 56.9 mm (Kaye and Obstfeld, 1989). Many observations exceeded the test ceiling (i.e., were recorded as NPC < 4.5 cm), resulting in a skewed frequency distribution. A test of normality showed the data to be significantly different from a normal distribution ($p = 0.006$ for the amplitude, and $p = 0.02$ for the difference between break and recovery point) and non-parametric statistics were therefore used. The descriptive statistics are given in Table 8.14.

variable	group	N	median	min.	max.
NPC break point	control	43	47.7	9.8	47.7
	dyslexic	38	47.7	15.0	47.7
NPC break-recov.	control	43	0	-5.9	16.1
	dyslexic	38	0	-4.0	14.1

Table 8.14 Descriptive statistics for near point of convergence subjective break point and relative recovery point (in Δ). "N" is total number, "min." is minimum, and "max." is maximum. A negative relative recovery indicates that the recovery occurred during over-convergence when the target was closer to the subjective than at the break point.

The hypothesis that the near point of convergence would be more distal in the dyslexic group was not supported, although there was a non-significant tendency in this direction (Mann-Whitney U test, 2-tailed, corrected for ties; $p = 0.54$). The distance between the break and recovery points was not significantly different between the 2 groups (Mann-Whitney U test, 2-tailed, corrected for ties; $p = 0.96$).

8.3.3.5 AC/A Ratio

The data for this section were complete, except for the strabismic subject (d03). The descriptive statistics are given in Table 8.15 and the hypothesis that the dyslexic group would have a higher AC/A than the control group was not supported (unpaired t-test, 2-tailed, $p = 0.68$; Mann-Whitney U test, 2-tailed,corrected for ties; $p = 0.78$).

group	N	mean	SD	min.	max.
control	43	3.1	1.2	0.7	6.0
dyslexic	38	3.2	1.3	0.7	8.0

Table 8.15 Descriptive statistics for the AC/ A, in Δ/D. "N" is total number, "SD" is standard deviation, "min." is minimum, and "max." is maximum.

8.3.3.6 Foveal Suppression

The results of the Mallett Unit Binocular Status Test were available for all subjects. The minimum angle of resolution in minutes of arc was converted to its logarithm and the difference between the values for the right and left eyes was calculated. A test of normality showed that this variable was not normally distributed (p = 0.018). The Mann-Whitney U test, therefore, was used to compare the 2 groups, and this showed that they did not differ significantly (2-tailed, p = 0.50). The relationship between foveal suppression and vergence amplitude and stability is investigated in Section 8.3.3.9.

Anisometropia and amblyopia are potential confounding variables to the results of the test of foveal suppression. Section 8.3.2.1, however, showed that the near V/A inter-ocular difference (wearing any correction that was worn for the foveal suppression test) was not significantly different in the 2 groups. The role of these confounding variables is further negated in Section 8.3.8.2.

8.3.3.7 Prism Vergences at Near

Several subjects were unable to appreciate a subjective blur point but the results for the break and recovery points were complete, except for the strabismic subject (d03). The data closely approximated a normal distribution.

Negative Prism Vergences

The descriptive and comparative statistics for these variables are summarised in Table 8.16. Clearly, the negative prism vergences (blur, break, and recovery points) were significantly reduced in the dyslexic group relative to the controls.

variable	group	N	mean	SD	min.	max.	p
base in blur	control	19	14.2	7.4	5.0	40.0	0.007
	dyslexic	24	9.5	4.5	1.0	19.5	
base in break	control	43	16.1	6.2	7.5	40.0	0.03
	dyslexic	38	13.6	5.4	4.5	26.0	
base in recovery	control	43	11.6	7.0	2.0	40.0	0.04
	dyslexic	38	9.1	5.3	-4.0	25.0	
base in break-recovery	control	43	4.5	2.9	0.0	13.5	0.50
	dyslexic	38	4.5	3.4	1.0	14.5	

Table 8.16 Descriptive and comparative statistics for negative prism vergences (in Δ). "N" is total number, "SD" is standard deviation, "min." is minimum, and "max." is maximum. The "variable" column refers to the blur, break, and recovery points, and the difference between the break and recovery point. A negative value in the recovery rows indicates that the subject required base out prism to regain fusion. The "p" values in the right hand column were calculated from the unpaired t-test (1-tailed).

Positive Prism Vergences

The descriptive and comparative statistics for these variables are summarised in Table 8.17. These data support the hypothesis that the positive prism vergences are relatively reduced in the dyslexic group.

variable	group	N	mean	SD	min.	max.	p
base out blur	control	16	16.7	9.6	0.0	35.8	0.025
	dyslexic	15	10.9	5.4	2.3	20.0	
base out break	control	43	19.0	7.8	5.7	37.0	0.015
	dyslexic	38	15.4	6.7	3.7	28.5	
base out recovery	control	43	12.3	8.1	1.0	32.0	0.044
	dyslexic	38	9.5	6.5	-1.0	24.5	
base out break-recovery	control	43	6.7	4.3	-2.3	20.0	0.20
	dyslexic	38	6.0	9.5	1.5	14.0	

Table 8.17 Descriptive and comparative statistics for positive prism vergences (in Δ). "N" is total number, "SD" is standard deviation, "min." is minimum, and "max." is maximum. The "variable" column refers to the blur, break, and recovery points and the difference between the break and recovery point. A negative value in the recovery rows indicates that the subject required base in prism to regain fusion. The "p" values in the right hand column were calculated from the unpaired t-test (1-tailed).

Prism Vergence Amplitude

The prism vergence amplitude was calculated as the difference between the base out and base in break and recovery points, in prism dioptres. It was not calculated for the blur points due to the small number of available results for this measurement. The descriptive and comparative statistics for the prism vergence amplitude are given in Table 8.18. These data strongly support the hypothesis that the prism vergence amplitude is relatively reduced in the dyslexic group.

variable	group	N	mean	SD	min.	max.	p
break out to in	control	43	35.1	10.7	15.5	59.0	0.0042
	dyslexic	38	29.0	9.5	8.5	52.5	
recovery out to in	control	43	23.9	11.5	7.5	56.5	0.013
	dyslexic	38	18.5	9.6	3.0	49.5	

Table 8.18 Descriptive and comparative statistics for prism vergence amplitudes (in Δ). "N" is total number, "SD" is standard deviation, "min." is minimum, and "max." is maximum. The "variable" column refers to the amplitude between the base out and base in break points (row 2) and recovery points (row 3). The "p" values in the right hand column were calculated from the unpaired t-test (1-tailed).

8.3.3.8 Stereopsis

The results exhibited a skewed frequency distribution, even when when the Titmus Test was used at 80 cm, with many subjects achieving the test ceiling of 20". A test of normality confirmed that the data differed significantly from a normal distribution ($p = 0.001$), and the appropriate descriptive statistics are given in Table 8.19. In view of the literature in Section 2.4, one-tailed comparative statistics again seemed appropriate. The hypothesis that the stereopsis of the dyslexic group would be reduced compared with the controls was not supported (Mann-Whitney U test, 1-tailed, corrected for ties; $p = 0.19$).

group	N	median	min.	max.
control	43	20	20	400
dyslexic	39	25	20	400

Table 8.19 Descriptive statistics for the Titmus stereopsis test in seconds of arc. "N" is total number, "min." is minimum, and "max." is maximum.

8.3.3.9 Secondary Analyses

Refractive and Binocular Vision Test Results

The relationship between the mean SER and the prism vergence amplitude was investigated by calculating the Spearman correlation co-efficient. This was not significant, either for each group separately or for both together (2-tailed $p > 0.10$). Similarly, the relationship between the mean SER and the dissociated vergence stability was not significant for either group or both together (2-tailed $p > 0.10$).

A binocular vision anomaly can impair binocular V/A (Pickwell, 1989; p. 42). Hence, the relationships between the binocular near V/A and the difference between the best monocular V/A and binocular V/A at near and the vergence amplitude and stability were investigated (*see* Table 8.20).

Although lower vergence amplitudes were significantly correlated with poorer binocular near V/As for the dyslexic group and both groups combined, the difference between best monocular and binocular near V/As was not significantly associated with the vergence amplitudes. This supports the conclusion in Section 8.3.2.4 that the worse binocular acuities in the dyslexic group were not caused by vergence dysfunction.

The only significant correlation concerning dissociated vergence stability was that in the control group worse binocular near V/A was related to greater degrees of dissociated vergence instability. This puzzling finding could be an artifact due to the relatively small number of control children who exhibited vergence instability.

variables	group	correlation	
		r_s	p
binocular near V/A **and** vergence ampl.	both	-0.202	0.035
	control	0.051	0.48
	dyslexic	-0.420	0.0052
binocular near V/A **and** vergence stabil.	both	0.309	0.38
	control	0.348	0.012
	dyslexic	0.169	0.15
binocular V/A supremacy **and** vergence ampl.	both	-0.076	0.25
	control	-0.095	0.27
	dyslexic	0.008	0.48
binocular V/A supremacy **and** vergence stabil.	both	0.112	0.16
	control	0.115	0.23
	dyslexic	0.094	0.28

Table 8.20 Correlation between 2 V/A variables and 2 binocular vision variables (individually). "binocular near V/A" is the logMAR acuity whilst wearing any refractive correction normally used in class (negative values represent better V/A), "binocular V/A supremacy" is the difference between the best monocular presenting near V/A and the binocular equivalent (positive values indicate that the binocular acuity was better than the best monocular), "vergence stabil." is the stability of response (in Δ) on the Maddox Wing Test (larger values indicate less stability), and "vergence ampl." is the prism vergence amplitude (in Δ). "r_s" represents the Spearman correlation co-efficient (corrected for ties), the significance of which (1-tailed) is given by the adjacent "p" value.

Vergence Amplitude and Vergence Stability

Spearman correlation co-efficients (corrected for ties) were calculated to investigate the relationship between the vergence amplitude and dissociated vergence stability. The majority of control subjects did not demonstrate any instability on the Maddox wing test, and it is not surprising, therefore, that the Spearman correlation co-efficient for this group did not reach significance (r_s = -0.152, 1-tailed p = 0.16). However, these variables were significantly correlated in the dyslexic group (r_s = -0.30, 1-tailed p = 0.033) and both groups combined (r_s = -0.253, 1-tailed p = 0.012).

Foveal Suppression and Vergence Amplitude and Stability

The relationship between both the vergence amplitude and dissociated stability and foveal suppression was investigated using Spearman correlation co-efficients (*see* Table 8.21). Although the vergence amplitude was not significantly correlated with the degree of foveal suppression, there was a tendency for greater vergence instability to be associated with increasing foveal suppression. This finding approaches significance for the combined groups, and this was attributable to a highly significant correlation in the dyslexic group.

variables	group	correlation	
		r_s	p
foveal suppres. **and** vergence amplitude	both	-0.06	0.31
	control	0.03	0.42
	dyslexic	-0.11	0.26
foveal suppres. **and** vergence stability	both	0.15	0.092
	control	-0.13	0.45
	dyslexic	0.40	0.0071

Table 8.21 The correlation between foveal suppression ("foveal suppres.") and both prism vergence amplitude and dissociated vergence stability. The derivation of the foveal suppression is given in Section 8.3.3.6. "r_s" represents the Spearman correlation co-efficient (corrected for ties), the 1-tailed significance of which is given by the adjacent "p" value.

8.3.3.10 Summary

The dyslexic group demonstrated lower prism vergences, particularly the prism vergence amplitude, and relatively unstable motor stability with the near dissociation test; these findings may be summarised as reduced vergence amplitude and stability. There were no significant differences between the 2 groups in the results of the other tests in this section.

The significant binocular vision results were not associated with the spherical refractive error, but were related to the binocular near V/A (although probably not causally). The vergence instability was positively correlated with a measure of foveal suppression in the dyslexic group. It may be concluded that this section has demonstrated evidence of sub-clinical vergence dysfunction in the dyslexic group.

8.3.3.11 Discussion

Giles (1960; p. 464-467) described "binocular instability", which resulted in an unstable response in the Maddox wing test. He gave 2 causes of this condition, "fusion deficiency" and poor general health. He described fusion deficiency as a combination of increased heterophoria and decreased vergence amplitudes, and he regarded the resultant binocular instability as midway between heterophoria and heterotropia. Gibson (1955; p.330 and 385-394) stated that a low prism vergence amplitude may lead to binocular instability.

Binocular instability seems to be synonymous with decompensated heterophoria (Stidwill, 1990; p. 72); Pickwell (1989; p. 8) also linked decompensated heterophoria with atypical prism vergences. It has been suggested that decompensated heterophoria normally results in an associated heterophoria (Mallett, 1983), although experimental evidence suggests that this may not be the case (Sheedy and Saladin, 1983); this could be because the Mallett Unit measures physiological fixation disparity as well as associated heterophoria (Pickwell, 1984b and 1991). The present study did not find any difference between the groups in the dissociated heterophoria, or the type, degree, and stability, of the associated heterophoria (cf., Holland, 1987). Pickwell (1989, p. 32) pointed out that high degrees of dissociated heterophoria are often compensated, and low degrees uncompensated, and that the degree of the dissociated heterophoria may not be related to the presence of symptoms.

Foveal suppression can occur in decompensated heterophoria (Pickwell, 1989; p. 41) and, although this was equally common in both groups, it was significantly correlated with the degree of dissociated vergence instability in the dyslexic group. When foveal suppression does occur, it normally relieves any symptoms from the decompensated heterophoria (Mallett, 1988), and it seems likely that it would eliminate any detrimental effect that the heterophoria may be having on binocular V/A.

Other factors that can affect the degree of compensation of a heterophoria include: worry and anxiety, emotional and temperamental problems, refractive error, and accommodative anomalies (Pickwell, 1989, p. 7-8; Stidwill, 1990, p. 72-73). The first 2 factors cannot be ruled out, although the vergence amplitude and stability were not related to the refractive error (Section 8.3.3.9) or amplitude of accommodation (Section 8.3.4.1). Symptoms of decompensated heterophoria include asthenopia, intermittent diplopia and confusion, loss of stereopsis, rarely vertigo and nausea, and occasional blurring of vision caused by the running together of letters or objects (Giles, 1960, p. 464-5; Stidwill, 1990, p. 72-73). The incidence of some of these symptoms in the 2 groups are discussed in Section 8.3.9.3.

To summarise, the presence of significantly reduced prism vergences, which were linked to dissociated vergence instability, may represent features of binocular instability, or decompensated heterophoria. The former term may be more appropriate, since it seems that in the present sample the condition results from a lack of prism vergences to compensate for a relatively normal degree of heterophoria. It should be noted that the similarities between the 2 groups in the results of most of the routine clinical tests in this section suggest that the significant findings represent a sub-clinical difference, which may not, according to normal criteria, be expected to produce many more symptoms in the dyslexic group.

8.3.4 Tests of Accommodation

8.3.4.1 Amplitude of Accommodation

Primary Analyses

The results of this test were obtained in dioptres, and data were absent for 1 subject (b21), due to inattentiveness. The data for the 2 monocular conditions were normally distributed ($p = 0.14$ and 0.10 for right and left eyes respectively), but that for the binocular condition significantly differed from a normal distribution ($p = 0.045$). Non-parametric statistics were therefore used for all analyses relating to the amplitude of accommodation. The descriptive and comparative statistics (*see* Table 8.22) support the hypothesis that the amplitude of accommodation was reduced in the dyslexic group.

eye	group	N	median	min.	max.	p
right	control	43	16.8	8.8	21.0	0.0007
	dyslexic	39	14.0	4.0	21.0	
left	control	43	18.0	7.5	21.0	0.00016
	dyslexic	39	13.9	4.0	21.0	
both	control	43	20.0	9.0	21.0	0.0003
	dyslexic	39	16.0	4.0	21.0	

Table 8.22 Descriptive and comparative statistics for accommodative amplitudes (in D). "N" is total number, "min." is minimum, and "max." is maximum. The "p" values in the right hand column were calculated using the Mann-Whitney U test (1-tailed, corrected for ties).

Secondary analyses

The amplitude of accommodation was measured in this study with the refractive correction (if any) that the child normally wore in class. A low amplitude of accommodation could have been caused, therefore, by an uncorrected refractive error; this was investigated by calculating the Spearman correlation co-efficient between the binocular amplitude of accommodation and the SER. This correlation was not significant for either group individually or both combined (1-tailed $p > 0.10$). A low amplitude of accommodation was significantly correlated with worse near V/A in the combined groups ($r_s = -0.268$, 2-tailed $p = 0.016$) but this did not reach significance in the control ($r_s = -0.181$) or dyslexic groups individually ($r_s = -0.16$). The particularly low correlation in the dyslexic group suggests that the worse V/A in this group was not the result of poor accommodation.

Convergence is closely linked to accommodation (Bennett and Rabbetts, 1984, p. 161) and the correlations between the binocular amplitude of accommodation and both the near point of convergence and prism vergence amplitude were investigated. A dissociated vergence instability may be linked to the prism vergence amplitude (*see* Section 8.3.3.11, and this was included in these analyses (*see* Table 8.23).

correlation between:	group	correlation	
		r_s	p
binocular amp. accomm. & NPC	both	0.482	<0.00003
	control	0.379	0.007
	dyslexic	0.614	0.0001
binocular amp. accomm. & vergence amp.	both	0.326	0.0018
	control	0.231	0.067
	dyslexic	0.426	0.0048
binocular amp. accomm. & vergence stabil.	both	-0.173	0.061
	control	-0.174	0.13
	dyslexic	-0.082	0.31

Table 8.23 Regression of binocular amplitude of accommodation ("binocular amp. accomm.") on 3 binocular vision variables. "NPC" is the near point of convergence (Δ), "vergence amp." is prism vergence amplitude, and "vergence stabil." is the stability of response (Δ) on the Maddox wing test. "r_s" represents the Spearman correlation co-efficient (corrected for ties), the 1-tailed significance of which is given by the adjacent "p" value.

Table 8.23 shows a highly significant direct correlation between the amplitudes of accommodation and convergence in the separate and combined groups, and a similar link between accommodative amplitude and prism vergence amplitude in the dyslexic and combined groups. The border-line significance of the latter correlation in the control group may be due to the relatively small variation of both variables in this group. There was a tendency for lower amplitudes of accommodation to be correlated with increased vergence instability; this only approached significance for the combined groups.

8.3.4.2 Accommodative Lag

The results of this test were absent for 1 subject (b22), due to inattentiveness. The descriptive and comparative statistics for the accommodative lag are given in Table 8.24. These data do not support the hypothesis that there would be an increased accommodative lag in the dyslexic group.

eye	group	mean	SD	p
right	control	0.96	0.31	0.471
	dyslexic	0.96	0.38	
left	control	0.98	0.39	0.343
	dyslexic	1.02	0.42	

Table 8.24 Descriptive and comparative statistics for accommodative lag (in dioptres). "SD" is standard deviation and the 1-tailed "p" values in the right hand column were calculated using the unpaired t-test.

The lack of a significant finding for this test, in contrast to the results for the accommodative amplitude, suggests that these 2 tests assess different variables. This was confirmed by the Spearman correlation co-efficient using the combined data from both groups. A higher accommodative amplitude was associated with less accommodative lag, but this only reached significance for the right eye, with a Spearman rho (corrected for ties) of 0.195 for the right eye and 0.083 for the left.

8.3.4.3 Dynamic Assessment of Accommodation and Convergence

It was only after the first few subjects had been examined that the control condition of this test was introduced; hence, the control condition results for 3 subjects (d21, d22, d31) were absent. The data were considered in 2 forms. Firstly, the number of half cycles achieved in 30, 60, and 90 seconds for the experimental (distance-near, or DN) condition were analysed. Secondly, these 3 values were divided by the number of half cycles achieved in the appropriate time for the control (near only, or N) condition. This gave a ratio of the speed of 4 digit number reading with and without changing accommodation and vergence. The descriptive and comparative statistics (*see* Table 8.25) show that the dyslexic group were significantly slower at the DN task, but performed slightly faster at the DN task relative to the N task. Since this latter finding is contrary to the hypothesis, the one-tailed p-values in Table 8.25 should be doubled to give 2-tailed values (significance is then lost).

variable	group	N	mean	SD	min.	max.	p
DN in 30 s	control	43	12.3	2.9	6	18	0.0001
	dyslexic	37	8.6	2.8	2	14	
DN in 60 s	control	43	22.0	4.5	13	31	0.0001
	dyslexic	37	15.0	5.0	3	25	
DN in 90 s	control	43	31.4	7.5	15	47	0.0001
	dyslexic	37	21.2	6.9	5	34	
DN/N in 30 s	control	43	0.853	0.151	0.6	1.364	0.31*
	dyslexic	34	0.872	0.183	0.333	1.222	
DN/N in 60 s	control	43	0.788	0.101	0.607	1.000	0.19*
	dyslexic	34	0.814	0.151	0.364	1.091	
DN/N in 90 s	control	43	0.760	0.093	0.565	1.026	0.03*
	dyslexic	34	0.808	0.122	0.583	1.063	

Table 8.25 Descriptive and comparative statistics for the dynamic test of convergence and accommodation. "DN in 30 s" refers to, for example, the number of half cycles achieved in the condition involving vergence and accommodation achieved in 30 seconds; similarly "DN/N in 60 s refers to the number of half cycles achieved in 60 seconds in the vergence and accommodation condition divided by the number achieved in the near only condition. "N" is total number, "SD" is standard deviation, "min." is minimum, and "max." is maximum. The "p" values in the right hand column were calculated using the unpaired t-test. * these figures should be doubled to obtain 2-tailed values (*see* text).

The slower reading speed of the dyslexic group resulted in a slower performance at both the N and DN conditions and all subjects were almost invariably faster at the N condition because no vergence and accommodation were required. Hence, a reduced reading speed should have a relatively greater slowing effect at the N condition and the dyslexic children should be relatively faster at the DN condition. This explains why the ratio of DN to N performance shows a non-significant tendency to be greater in the dyslexic group.

8.3.4.4 Summary

The dyslexic group had significantly lower amplitudes of accommodation than the control group, although this did not seem to impair their accommodative lag or performance at a dynamic accommodative task. The lower amplitudes of accommodation were not related to the near V/As or SER, but were closely positively correlated with the vergence amplitudes.

8.3.4.5 Discussion

Poynter et al. (1982) found an increased accommodative lag in subjects with a reading disability; the present study used a similar technique, but failed to support this finding. These results suggest that the tests of accommodative lag, facility, and amplitude measure different functions. Wick and Hall (1987) investigated the inter-test relationship of 3 accommodative tests, which were similar to those in the present study, on 200 school children and also found that, according to their criteria, many children "failed" at only 1 of the tests. They used these findings to suggest that all 3 tests should be used clinically, although they did not relate their results to symptoms.

Convergence and accommodation are closely linked (Bennett and Rabbetts, 1984, p. 161), and recent research suggests that the 2 are even strongly correlated in young infants (Riddell et al., 1991). The link between reduced accommodative and vergence amplitudes in the present study could be causal (in either direction), or owing to a non-causal association; however, the reduced monocular amplitude of accommodation in the dyslexic group is unlikely to be linked to poor convergence. The suggestion in Section 8.3.3.11 that binocular instability in the dyslexic group could be caused by a decreased amplitude of accommodation may be supported,therefore, by the results of the tests of accommodation.

8.3.5 Modified Dunlop Test

8.3.5.1 The Data

The key results that were obtained for the modified Dunlop Test were the stability of ocular reference (recorded as an integer between 5 and 10) and which eye was the referent eye (right, left, or both). These data were unavailable for 3 of the subjects: subject d03, who was strabismic; subject d04, an amblyope who completely suppressed the right eye;

and subject d32, who reported that both targets moved on every occasion.

Shortly after the study had started, it was decided to collect 2 further details. On some trials a fixation disparity was present before base in prism was introduced. In these cases the eye in which the fixation disparity occurred was still taken to be the non-referent eye, but a note was made of the frequency with which prisms were required to produce the fixation disparity (this was described as "frequency divergence required"). A measure of this variable was available for 41 members of the control group and 32 of the dyslexic group. Secondly, the experimenter gave a subjective score (from 0 to 5) for the quality of response. This was necessary because some subjects always reported that one particular monocular marker moved, or that they alternated, despite the reversals of the polaroid filters and verbal instructions that the response would be unpredictable. A measure of this variable was available for 36 and 30 members of the control and dyslexic groups respectively.

8.3.5.2 Primary Statistical Analyses

A normality test showed that the data for the stability of reference eye and quality of response were not normally distributed (p = 0.035 and 0.008, respectively), but that the frequency that divergence was required was normally distributed (p = 0.5). The relevant descriptive and comparative statistics for these variables are given in Table 8.26. Neither the stability of the reference eye nor the frequency with which divergence was required were significantly different in the 2 groups, although the dyslexic group seemed to be less reliable witnesses.

variable	group	centre	SD	p
stability of reference eye	control	7		0.204†
	dyslexic	7		
frequency diverg. required	control	8.32	3.41	0.80*
	dyslexic	8.13	3.18	
quality of response	control	3		0.019†
	dyslexic	3		

Table 8.26 Descriptive and comparative statistics for the modified Dunlop Test. The variables are explained in the text. "centre" represents the measure of central tendency; this was the mean for the second variable and the median for the first and last variables. The key for the comparative statistics that were used to arrive at the "p" values in the right hand column is:

* unpaired t-test (2-tailed)

† Mann-Whitney U test (2-tailed, corrected for ties).

Classification as "Fixed" or "Unfixed" Reference

Most of the recent research relating to the Dunlop Test has used the Stein and Fowler (1981) classification of the result as "fixed", when the same eye was the referent eye 8 or more times out of 10, or "unfixed" (*see* Section 3.4). This system may be useful clinically but statistical power is lost when a discrete interval scale is converted to a binary nominal scale. The data, however, were transformed to this binary classification so that the results could be compared with those of other workers. This transformation revealed that 60.5% of the control and 80.6% of the dyslexic group had "unfixed" reference; this was of border-line significance (chi-square with continuity correction, $p = 0.091$).

Results Obtained Under Forced Vergence

Stein (1991b) suggested that a different result was obtained on the Dunlop Test when the eyes were forced to diverge compared to when a natural fixation disparity occurred in the primary position. The data were therefore re-analysed when those subjects who, for any of the trials, had not required prism to produce the divergence were excluded (Table 8.27). There were 30 control and 19 dyslexic children in these new groups. The referent eye was less fixed in the dyslexic group and this just reached significance using the discrete interval scale; it failed to reach significance, however, when the Stein and Fowler (1981) binary nominal classification was used. The quality of response was again significantly poorer in the dyslexic group. These results appear to be similar to those obtained using all the available data and the full set of results, therefore, will be used in subsequent analyses.

variable	group	p
stability of reference eye	control	0.048
	dyslexic	
quality of response	control	0.0088
	dyslexic	
stable/ unstable	control	0.14
	dyslexic	

Table 8.27 Comparative statistics for the forced vergence results of the modified Dunlop Test. The variables in the first 2 rows are explained in the text and the last row is the stability using the Stein and Fowler (1981) binary classification. The key for the comparative statistics that were used to arrive at the "p" values in the right hand column is:
* Mann-Whitney U test (2-tailed, corrected for ties)
† Chi-square with continuity correction.

8.3.5.3 Secondary Analyses

The hypothesis that an unfixed reference eye was associated with vergence dysfunction was investigated in 2 ways. Firstly, the Spearman correlation co-efficients between 3 binocular vision variables and the stability of the reference eye (using the discrete interval scale) were calculated. The results are given in Table 8.28, and these do not support the hypothesis, either for both groups together or for each separately.

variables	group	correlation	
		r_s	p
Dunlop Test	both	0.045	0.48
stability &	control	0.005	0.49
vergence stabil.	dyslexic	0.079	0.47
Dunlop Test	both	0.045	0.35
stability &	control	-0.077	0.31
vergence amp.	dyslexic	0.158	0.17
Dunlop Test	both	0.092	0.21
stability &	control	0.077	0.31
NPC break	dyslexic	0.091	0.30

Table 8.28 Correlation between stability of response in Dunlop Test and 3 binocular vision variables. "vergence stabil." is the stability of response at the Maddox wing test (in Δ), "vergence amp." is vergence amplitude, and "NPC break" is the near point of convergence on the RAF rule. "r_s" represents the Spearman correlation co-efficient, the 1-tailed significance of which is given by the adjacent "p" value.

The second method of investigating this hypothesis was to use the Stein and Fowler (1981) classification of the Dunlop Test result to place subjects in sub-groups with a "fixed" or "unfixed" referent eye. The appropriate comparative statistics were then used to investigate whether each of the binocular vision variables in Table 8.28 was different distributed in the 2 sub-groups within the dyslexic, control, or combined groups. None of these analyses approached significance (1-tailed $p > 0.10$).

8.3.5.4 Summary and Discussion

The requirement for base in prism to produce a fixation disparity in the modified Dunlop Test was not significantly different between the 2 groups. There was a tendency, of border-line significance, for the dyslexic group to exhibit less fixed ocular reference, and the significance of this was similar when the subjects who did not need prism to induce a fixation disparity were excluded. Forced divergence is extremely unnatural and the data obtained under normal binocular viewing, therefore, were included in subsequent analyses. A subjective grading suggested that the dyslexic group gave a significantly less reliable response than the controls. There were no significant correlations between a more fixed referent eye and the vergence stability or amplitude. This contradicts the results of , and may suggest that the use of the term "binocular instability" to describe unstable results on the Dunlop Test (Stein, 1991a) is undesirable.

It was noted in Section 3.4 that the Dunlop Test is sensitive to the confounding variable of subject intelligence. The results in this section also suggest that, even within groups of matched IQ, performance at this test is strongly influenced by the quality of the subject's response.

8.3.6 Pattern Sensitivity

8.3.6.1 The Data

Results in this section were successfully obtained for all subjects and the data were available in 2 forms. Firstly, the presence or absence of each type of anomalous effect was scored using a binary nominal scale (i.e., "1" if an anomalous effect was seen, and "0" if it was not). Hence, a measure of pattern glare was calculated as the total number of illusions seen on viewing the experimental grating, and this was compared with the equivalent sum on viewing the control grating. These are described below as "integer scores".

Whilst this method has the advantage of compatibility with the work of Wilkins and colleagues (*see* Section 4.4.2), the lack of intra-measurement quantification does not make full use of the control condition. For example, a subject who reported a considerable blurring of the experimental pattern and a minimal blurring of the control pattern would receive the same score ("1") for both. Further information, therefore, was gathered concerning the severity of the anomalous visual effects (*see* Section 7.4.7). It seemed appropriate that the scoring of this should attach greater importance to the difference between the presence of an anomalous effect than to its severity; a disadvantage was that an arbitrary decision had be made about how this was achieved. The method that was adopted gave a value of 0 to the absence of an illusion, 1.0 to the presence of a "mild" anomalous visual effect, and 1.1 if it was described as "moderate". A score of 1.3 was reserved for an anomalous effect that made the subject unwilling to view the pattern (this classification was not required in the present study). Scores collated in this way are described in the analyses below as "real scores".

8.3.6.2 Primary Analyses

The total number of anomalous effects observed by a subject for each condition was calculated from the "absolute" scores. The difference between this total for each condition was obtained; this represented how many more illusions were seen when viewing the experimental grating than the control. Finally, using the "real" scores, an equivalent value was obtained for the presence and severity of anomalous visual effects with the experimental relative to the control grating. The final variables can thus be described and abbreviated as:

- *integer* sum of number of illusions seen when viewing control grating (integer sum control)
- *integer* sum of number of illusions seen when viewing experimental grating (integer sum experimental)
- *integer* difference between number of illusions seen when viewing experimental and control grating (integer difference)
- *real* difference between number of illusions seen when viewing experimental and control grating (real difference)

The first variable in the above list differed significantly from a normal distribution ($p = 0.001$), whilst the other 3 approximated to a normal distribution ($p = 0.13$, 0.11, and 0.17). The appropriate descriptive and comparative statistics for these variables are given in Table 8.29.

variable	group	centre	spread	p
integer sum	control	0	2	0.028†
control	dyslexic	1	5	
integer sum	control	2.88	1.65	0.017*
experimental	dyslexic	3.74	1.53	(0.016)†
integer	control	2.40	1.53	0.36*
difference	dyslexic	2.72	1.73	(0.32)†
real	control	2.46	1.58	0.28*
difference	dyslexic	2.87	1.79	(0.13)†

Table 8.29 Descriptive and comparative statistics for the incidence of anomalous visual effects in the pattern glare test. The variable column is explained in the text, "centre" is the measure of central tendency (median for the first variable and mean for the others), and "spread" is the measure of spread (range for the first variable and standard deviation for the others). The key for the comparative statistics that were used to arrive at the "p" values in the right hand column is

* unpaired t-test (2-tailed)

† Mann-Whitney U test (2-tailed, corrected for ties).

The data in Table 8.29 show that whilst the dyslexic group reported significantly more anomalous visual effects than the control group on viewing the experimental pattern, they also reported more anomalous visual effects on viewing the control pattern. When the response to the experimental condition were considered relative to the control condition, the groups were not significantly different (although there was a tendency in the anticipated direction). The results, therefore, do not support the hypothesis that pattern glare occurs more often in the dyslexic group.

8.3.6.3 Secondary Analyses

The hypothesis that pattern glare is associated with vergence dysfunction was investigated by calculating the correlation co-efficient between the last 3 variables in Table 8.29 and the prism vergence amplitude (Pearson correlation co-efficient) and dissociated vergence stability (Spearman correlation co-efficient). These co-efficients were calculated for both subject groups separately and combined, and none of these were significant (2-tailed $p > 0.10$). This hypothesis was therefore not supported.

Similarly, the Spearman correlation co-efficients between the last 3 variables in Table 8.29 and the amplitude of accommodation were calculated for both subject groups separately and combined. All correlations were inverse (i.e., lower amplitudes of accommodation were associated with increased pattern glare), but none of these reached significance (2- tailed $p > 0.10$).

8.3.6.4 Summary and Discussion

When a grating that should cause "pattern glare" was viewed, the dyslexic group reported seeing more anomalous visual effects than the control group, but they also reported more of these illusions when viewing a control grating that should not have caused pattern glare. The 2 groups did not differ significantly in the number of illusions seen with the experimental relative to the number seen with the control grating. These results were not significantly correlated with the vergence and accommodative test results.

The technique of summing the number of anomalous visual effects that a subject reports is the only published method of quantifying pattern glare, but is highly subjective and does not appear to have been used with children before. In the present study it seems that the suggestion of anomalous visual effects on viewing a control grating was more powerful as any "pattern glare factor". The increased number of illusions seen by the dyslexic group with the control grating may suggest that they are more suggestible and it is possible that this effect could have masked a real increase in the number of illusions seen by the dyslexic group with the experimental grating. Wilkins (1990 and 1991b) reported that a test was being developed that may prove to be a more appropriate method of quantifying pattern glare in children. Using the test that is currently available, the present study has failed to discover a conclusive difference between the susceptibility of the 2 groups to pattern glare.

8.3.7 Investigations of Parallel Visual Processing

8.3.7.1 Spatial Contrast Sensitivity Function

The data for this test were successfully collected from all subjects. The distribution of the contrast sensitivities at each spatial frequency did not significantly depart from a normal distribution ($p > 0.05$), although the significance was borderline ($p < 0.10$) at all spatial frequencies other than 1 cycle/°. The log mean contrast sensitivity for the dyslexic and control groups at each spatial frequency was calculated, together with the standard deviation, and these are shown in Figure 8.3 and Table 8.30. Kennedy and Dunlap (1990) assessed the reliability of the Vistech contrast sensitivity test for repeated measures. They found an increased variation in low spatial frequency measurements; this agrees with the data in Table 8.30.

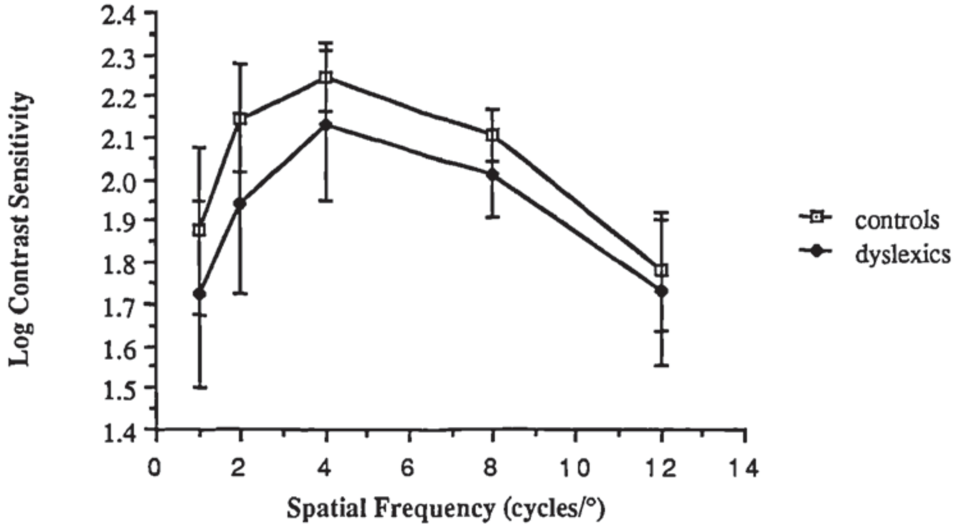

Figure 8.3 Graph of Spatial Frequency v. Log Contrast Sensitivity for the control and dyslexic groups. The points represent the mean value for each group, and the error bars are ± 1 standard deviation.

It can be seen from Table 8.30 that the control group had a significantly lower contrast sensitivity at all spatial frequencies except 12 cycles/°. The ratio of the contrast sensitivity at 1 cycle/° and 12 cycle/° was calculated, and this was also significantly lower in the dyslexic group (unpaired t-test, 1-tailed; p = 0.0029; Mann-Whitney U test, 1-tailed, corrected for ties; p = 0.0013). These data support the hypothesis that the low spatial frequency contrast sensitivity function was impaired in the dyslexic group, although they also demonstrated a depressed sensitivity at medium spatial frequencies (cf., Lovegrove et al., 1986b).

spatial freq.	group	mean	SD	p
1 (cycle/°)	control	1.876	0.199	0.0008
	dyslexic	1.723	0.223	(0.0009)
2 (cycle/°)	control	2.146	0.130	0.0001
	dyslexic	1.942	0.219	(<0.0001)
4 (cycle/°)	control	2.253	0.081	0.0002
	dyslexic	2.137	0.183	(<0.0001)
8 (cycle/°)	control	2.109	0.063	0.0001
	dyslexic	2.012	0.105	(<0.0001)
12 (cycle/°)	control	1.779	0.142	0.083
	dyslexic	1.729	0.177	(0.078)

Table 8.30 Descriptive and comparative statistics for spatial contrast sensitivity function (in log contrast sensitivity units). "Spatial freq." is spatial frequency and "SD" is standard deviation. The comparative statistics that were used to arrive at the "p" values in the right hand column were the unpaired t-test (1-tailed) and, in parentheses, the Mann-Whitney U test (1-tailed, corrected for ties).

Spatial Contrast Sensitivity and Vergence

To investigate the hypothesis that vergence dysfunction is associated with a relative reduction in low spatial frequency contrast sensitivity, a simple regression analysis was performed between the ratio of contrast sensitivity at 1 to 12 cycles/° and the prism vergence amplitude. When the data from the combined groups was analysed the regression was statistically significant (ANOVA based on a partition of the total sum of squares, 2-tailed, $p = 0.019$); those subjects with lowest fusional reserves demonstrated relatively worse low spatial frequency contrast sensitivity (*see* Figure 8.4).

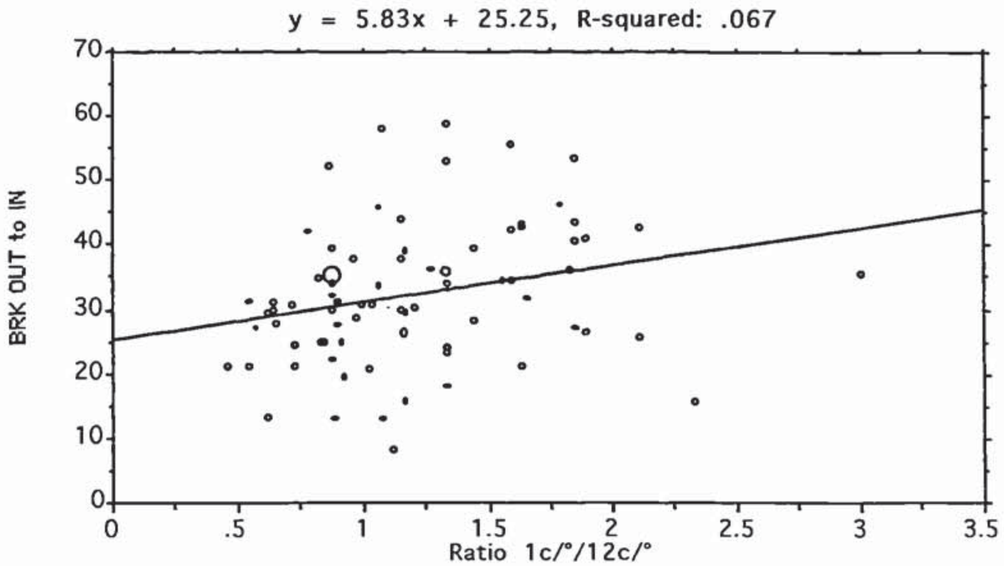

Figure 8.4 Scatter-graph of the ratio of contrast sensitivity at 1 to 12 cycles/° v. prism vergence amplitude ("break out to in"), in prism dioptres, for all subjects. Overlapping data are plotted as proportionately larger open circles.

A similar analysis for the dyslexic and control groups, separately, failed to reach significance, although there was a positive correlation in both cases (ANOVA, 2-tailed, $p = 0.18$ for the control and 0.34 for the dyslexic groups); the difference between the correlation co-efficients of the 2 groups was not significantly different (2-tailed, $p > 0.20$).

Spatial Contrast Sensitivity and Accommodative Amplitude

The Spearman correlation co-efficients between the ratio of contrast sensitivity at 1 to 12 cycles/° and the binocular accommodative amplitude were calculated. This correlation was not significant for each group separately or both groups combined (2-tailed $p > 0.10$).

Spatial Contrast Sensitivity and The Dunlop Test Results

The Spearman correlation co-efficients between the ratio of contrast sensitivity at 1 to 12 cycles/° and the stability of the referent eye on the modified Dunlop Test (recorded on a discrete interval scale) were calculated. These were not significant for both groups combined ($r_S = -0.011$) or for the control ($r_S = -0.213$, 2-tailed $p = 0.17$) or dyslexic ($r_S = 0.18$, 2-tailed $p = 0.28$) groups individually.

8.3.7.2 Temporal Contrast Sensitivity

Two members of the control group and 8 of the dyslexic group were unable to complete this test owing to a difficulty in perceiving the flicker. This, in most cases, resulted from anomalous visual effects, mainly the presence of "blobs" in the uniform green field of the flicker eyepiece. The reasons for this phenomenon, and for its increased incidence in the dyslexic group, are unknown. The data for the first 2 subjects (both dyslexic) were also excluded because a final modification was made to the instrument after they had been examined (an extra diffusing filter was inserted to eliminate a directional effect). The data for this variable were normally distributed.

The threshold for each subject was transformed into log units, and the descriptive and comparative statistics are given in Table 8.31. The range of measurements was from 0.08 to 0.38 Michelson contrast and the data in Table 8.31 strongly support the hypothesis that the dyslexic group show a reduced temporal contrast sensitivity.

variable	group	N	mean	SD	min.	max.	p
log flicker	control	41	-2.70	0.135	-3.10	-2.42	0.0005
threshold	dyslexic	29	-2.60	0.075	-2.77	-2.48	

Table 8.31 Descriptive and comparative statistics for log flicker threshold "N" is total number, "SD" is standard deviation, "min." is minimum, and "max." is maximum. The "p" value was calculated using the unpaired t-test (1-tailed).

The Relationship Between Spatial and Temporal Contrast Sensitivity

The hypothesis that temporal contrast sensitivity was measuring the same function as the low spatial frequency spatial contrast sensitivity was investigated in 2 ways. Firstly, the linear regression of log spatial contrast sensitivity at 1 cycle/° on log flicker threshold was calculated and tested, for both groups together and for each separately. Secondly, the linear regression of the ratio of contrast sensitivity at 1 to 12 cycles/° on log flicker threshold was calculated. The results of these regressions are given in Table 8.32.

regression of:	group	regression	
		r	p
log CSF at 1 c/° on log flicker	both	0.265	0.028
	control	0.065	0.70
	dyslexic	0.280	0.14
ratio CSF at 1 to 12 c/° on log flicker	both	0.183	0.13
	control	0.116	0.47
	dyslexic	0.386	0.039

Table 8.32 Regression of low spatial frequency contrast sensitivity on log temporal contrast threshold ("log flicker"). "r" represents the Pearson correlation co-efficient, the significance of which (2-tailed) is given by the adjacent "p" value (from ANOVA of partitioned sum of squares).

The direction of the significant relationships in Table 8.32 was tested graphically, and was in both cases as predicted (less sensitive spatial was associated with less sensitive temporal contrast sensitivity). All the correlations were low and, although the flicker threshold for all the subjects taken together was significantly correlated with absolute low spatial frequency contrast sensitivity, the significance was lost for the dyslexic group by itself. The dyslexic group did, however, demonstrate a significant relationship between the flicker sensitivity and relative low spatial frequency contrast sensitivity. The differences between the correlation co-efficients of each group for both of the regressions in Table 8.32 were not statistically significant (2-tailed, $p > 0.20$)

Temporal Contrast Sensitivity and Vergence Dysfunction

It was suggested in Section 5.3.2.8 that if the temporal contrast sensitivity at 10 Hz was a valid measure of transient system function, then this could be used to investigate whether the vergence dysfunction in dyslexia was linked to a transient system deficit. The correlation co-efficients between the flicker threshold and both vergence amplitudes and stability were calculated (*see* Table 8.33).

correlation	group	correlation	
		r	p
vergence amplitude and log flicker	both	-0.329	0.006
	control	-0.116	0.48
	dyslexic	-0.627	0.0004
vergence stability and log flicker	both	0.123	0.34
	control	0.011	0.99
	dyslexic	0.179	0.36

Table 8.33 Correlation between the log temporal contrast threshold ("log flicker") and both prism vergence amplitude and dissociated vergence stability. "r" represents: for the vergence amplitude the Pearson correlation co-efficient, the significance of which is given by the adjacent "p" value (2-tailed, from ANOVA of partitioned sum of squares); and for the vergence stability the Spearman correlation co-efficient, the 2-tailed significance of which is given by the adjacent "p" value.

For the combined groups, the vergence amplitude was significantly correlated with the flicker sensitivity (lowest vergence amplitudes were, as predicted, associated with less sensitive temporal contrast sensitivity); this correlation was attributable to a very significant relationship between these 2 variables in the dyslexic group (*see* Figure 8.5). Indeed, in the dyslexic sample approximately 40% of the variation in the vergence amplitudes can be accounted for by the variation in the flicker sensitivity. The difference between the correlation in the control group and that in the dyslexic group was statistically significant (2-tailed, p = 0.0074). The correlations between flicker threshold and vergence stability in Table 8.33 were not significant, although the trend was in the anticipated direction.

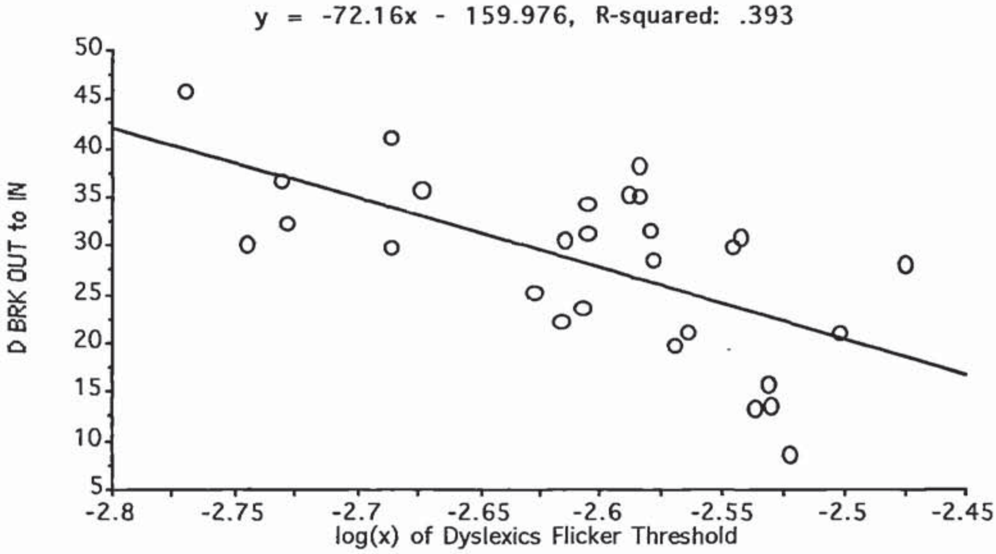

Figure 8.5 Regression of vergence amplitude ("D BRK OUT to IN"), in Δ, on log temporal contrast threshold for the dyslexic group. No points are hidden by overlap, and the equation of the regression line is given above the graph.

Temporal Contrast Sensitivity and Accommodative Amplitude

Spearman correlation co-efficients between the log temporal contrast threshold and binocular amplitude of accommodation were calculated. There was an inverse correlation that reached significance for both groups combined (r_S = -0.301, 2-tailed p = 0.012), but failed to reach significance in the dyslexic group (r_S = -0.295, 2-tailed p = 0.12) and in the control group (r_S = -0.142, 2-tailed p = 0.36).

Temporal Contrast Sensitivity and The Modified Dunlop Test Results

Spearman correlation co-efficients between the log temporal contrast threshold and stability of reference eye on the modified Dunlop Test (recorded on a discrete interval scale) were calculated. There were low inverse correlations that failed to reach significance for both groups combined (r_S = -0.048, corrected for ties) and for the control

(r_s = -0.07, corrected for ties) and dyslexic (r_s = -0.170, corrected for ties; 2-tailed p = 0.40) groups individually.

Temporal and Spatial Contrast Sensitivity and Pattern Glare

It was suggested in Section 5.3.2.8 that if the temporal contrast sensitivity at 10 Hz was a valid measure of transient system function then this could be used to investigate whether pattern glare in dyslexia is linked to a defect of the transient system. Three of the pattern glare variables, therefore, were regressed on the log flicker threshold (*see* Table 8.34); the pattern glare variables were explained more fully in Section 8.3.6.2.

regression of:	group	regression	
		r	p
integer sum experimental on log flicker thres.	both	0.014	0.91
	control	0.011	0.95
	dyslexic	0.40	0.034
integer difference on log flicker thres.	both	0.011	0.93
	control	0.10	0.54
	dyslexic	0.37	0.046
real difference on log flicker threshold	both	0.008	0.95
	control	0.087	0.59
	dyslexic	0.39	0.037

Table 8.34 Regression of 3 pattern glare variables on log flicker threshold ("log flicker thresh."). The variables are explained in the text. "r" represents the Pearson correlation coefficient, the significance of which is given by the adjacent "p" value (2-tailed, from ANOVA of partitioned sum of squares).

Table 8.34 shows that the number of anomalous visual effects reported when viewing a target that could cause pattern glare was significantly related to the temporal contrast sensitivity in the dyslexic group, but not in the other groups. This finding was still significant when criteria differences between the groups were taken into account by a control condition. The differences between the correlations for the control and dyslexic groups in Table 8.34 were not, however, statistically significant (2-tailed $p > 0.1$). The significant relationships were investigated graphically and were found to be contrary to the hypothesis, i.e., those dyslexic children who were less able to detect flicker tended to be those who experienced less pattern glare.

This finding was investigated further by looking at the relationship between the spatial contrast sensitivity function and pattern glare. The log contrast sensitivity at 1, 2, 4, 8, and 12 cycles/° and the ratio of contrast sensitivity at 1 to 12 cycles/° were individually regressed on the 3 pattern glare variables in Table 8.34. These correlations were not significant for the dyslexic group alone, or for the combined groups. There was a significant positive relationship between the number of illusions seen in the experimental condition of the pattern glare test and the log contrast sensitivity at 2 cycles/° for the control group (ANOVA based on a partition of the total sum of squares, 2-tailed, $p = 0.04$). The significance of this increased when the number of illusions seen in the control grating were subtracted ($p = 0.018$ for the integer and real number variables). It seems likely that these correlations, which were not significantly different from the equivalent correlations for the dyslexic group (2-tailed $p > 0.10$), represent an isolated chance observation.

It can be concluded that those dyslexic children in this study who were "better" at detecting flicker were more likely to experience pattern glare. This finding may relate to the interaction between fluorescent lighting and pattern glare (Wilkins and Neary, 1991). Wilkins and Neary (1991) suggested that pattern glare may be linked to an increased sensitivity to the flickering from fluorescent lighting (*see* Section 4.4.3), possibly owing to a defect of the transient system. Wilkins and Wilkinson (1991) proposed that visual discomfort from fluorescent lights may be reduced by tinted glasses that absorbed wavelengths in the green part of the spectrum and transmitted in the red. Wilkins (1991a) related this to the tonic suppression by diffuse red light of certain neurones, which may subserve the transient visual system, in the lateral geniculate nucleus. Wilkins' (1991a) theory, therefore, may provide a mechanism whereby the colour specific properties of the transient system result in a hypersensitivity to flicker being associated with pattern glare.

It is possible that, despite a "transient deficit" in the dyslexic group as a whole, there was a subgroup of dyslexic children with a hypersensitive transient visual system. Williams (1991b) has also hypothesised the existence of such a group and has used a questionnaire to link the symptoms of pattern glare with the use of red filters, which she believed selectively slowed and weakened the transient visual system. Whilst the present data support this hypothesis, the possibility of 2 dyslexic subgroups with a hyper- and hypo-sensitive transient system would need considerable theoretical and experimental support.

This hypothesis might predict a bimodal distribution of the flicker threshold. This was normally distributed in the combined groups and the frequency distributions in each group individually are illustrated in Figure 8.6. The data inconclusively suggests a bi-modal distribution of flicker threshold in the dyslexic group, although it should be noted that the "hypersensitive sub-group" had thresholds that approximated to the mean threshold in the control group.

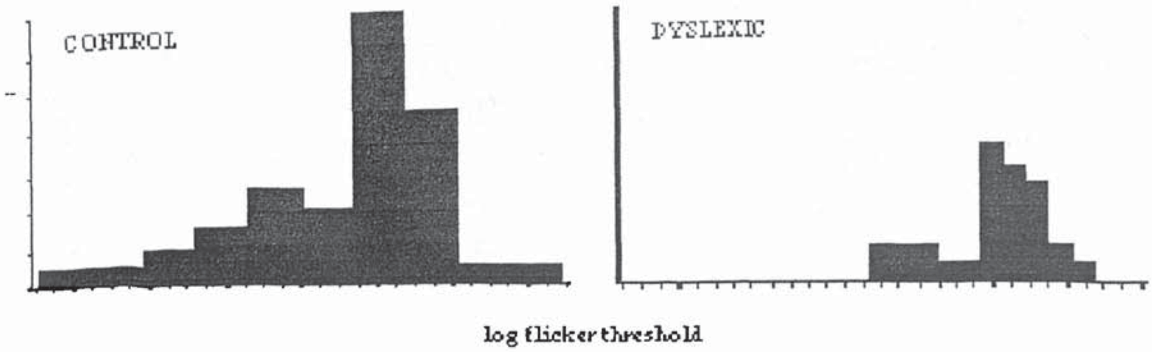

Figure 8.6 Frequency distributions of the log flicker threshold in the control and dyslexic groups. The vertical axis gives the number of subjects in each frequency grouping (from 0 to 14) and the horizontal axis scales are from -3.1 on the left to -2.4 on the right. The scales are the same in both graphs.

8.3.7.3 Summary

The dyslexic group performed significantly worse at both tests that were designed to measure transient system function, although the 2 were only loosely correlated. In the dyslexic group this "transient system deficit" was associated with decreased vergence and accommodative amplitudes and with a reduced manifestation of pattern glare.

8.3.7.4 Discussion

Lovegrove et al. (1982) compared the spatial contrast sensitivity function of poor readers with that of good readers and found that the poor readers had relatively: reduced sensitivity at low spatial frequencies, similar sensitivity at intermediate spatial frequencies, and slightly enhanced sensitivity at high spatial frequencies. The results of the present study differed in that the dyslexic group also demonstrated a relative reduction at intermediate spatial frequencies and a non-significant reduction at high spatial frequencies. The high spatial frequency results probably relate to the lower near V/As in the dyslexic group (*see* Section 8.3.2.1). Martin and Lovegrove (1984) showed that the intermediate spatial frequency differences are unlikely to result from differences in field size or illumination. Lovegrove et al. (1980a and 1982) investigated the effect of stimulus duration (from 40 ms to 1000 ms) on the contrast sensitivity function of SRD and control children. As the stimulus duration increased the maximum difference between the groups tended to shift away from the lower and towards the intermediate spatial frequencies. It seems likely, therefore, that the reduced sensitivity in the dyslexic group at intermediate as well as low spatial frequencies in the present study is attributable to the longer stimulus duration (real time) than that used by Lovegrove and colleagues.

The low correlation between the 2 supposed "tests of transient function" indicates that they do not measure the same variable. Merigan and Maunsell (1990) demonstrated that a lesion of the magnocellular layers of the lateral geniculate body in the macaque monkey did not impair contrast sensitivity for 2 cycle/° stationary gratings, but did effectively eliminate sensitivity to a very low spatial frequency 10 Hz flickering stimulus. The magno-cellular pathway is known to conduct visual information at high temporal rates and thus subserves the transient visual system. This is why it has been assumed in the present research that the flicker test is the most valid measure of transient function. Further research is needed to establish the precise relationship between this and the other tests that have been designed to measure transient function.

The high correlation between vergence amplitude and flicker sensitivity is interesting, although it cannot *prove* the hypothesis that feedback through the transient system plays a key role in vergence eye movements (*see* Section 9.2.2. It was suggested in Section 8.3.3.10 that the vergence instability is a sign of binocular instability resulting from the low prism vergence amplitudes. This hypothesis would anticipate a lower correlation between flicker threshold and vergence stability than between flicker threshold and vergence amplitude, and may explain why the former correlation did not reach significance.

The accommodative amplitude was correlated with flicker sensitivity, although this only reached significance for the combined groups. This finding is also discussed in Section 9.2.2. Cornelissen et al. (1991b) found that subjects with a less stable reference eye on the Dunlop Test had reduced spatial contrast sensitivity at 0.5 c/° but had better contrast sensitivity than his control group at 6 c/°. In the present study, however, the Dunlop Test results were neither related to the spatial nor temporal contrast sensitivity functions.

Within the dyslexic group there was a positive correlation between an improved ability to detect flicker and an increased incidence of pattern glare. This could be explained by a hypothesised dyslexic sub-group who have a *hyper*-sensitive transient visual system (*see* Section 4.4.4; more work is needed to investigate this hypothesis.

8.3.8 Visual Search Task

Two of the younger subjects (d14 and d35) became tired and failed to complete this test; their data were excluded. The mean monocular search times in each sub-test and for each condition were calculated for the 2 groups; these, and the equivalent binocular means are plotted in Figure 8.7. The order of presentation was the same for all subjects, but the 2 conditions were interwoven for various subtests so that the mean practice effect for each condition should have been similar. Comparisons between subject groups, therefore, are only valid for a given condition and subtest.

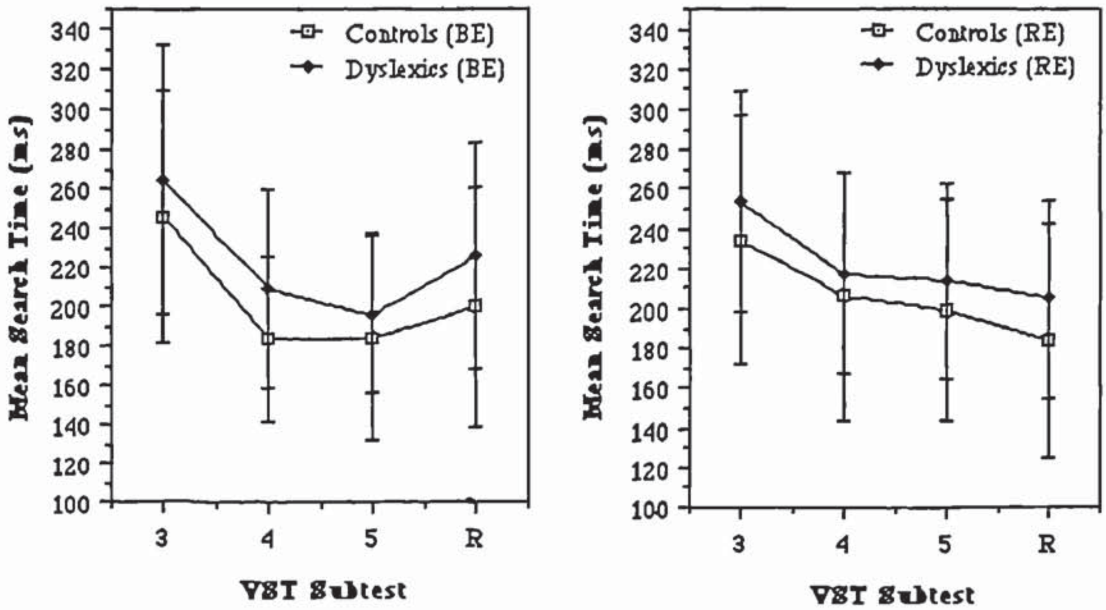

Figure 8.7 Graph of visual search task subtest v. mean search time (in milliseconds). The graph on the left refers to the binocular condition and that on the right to the monocular condition. In both graphs the open squares represent the control, and the closed circles the dyslexic subjects. The error bars are ± 1 standard deviation (*see* text).

The difference between the monocular search time (for all subtests) and the binocular search time was calculated and termed the "binocular factor". Higher positive values of this variable represented a quicker performance in the binocular condition. It was noted in Section 7.4.9.1 that the final subtest ("R") may induce pattern glare, whilst the other subtests should not. The mean time to complete subtest R was divided by the mean time to complete subtest 5; this subtest was used because it was of approximately equivalent difficulty to subtest R. This calculation was only carried out for the binocular condition and the resultant variable was termed the "crowding factor". Higher positive values of this variable signified that a subject was relatively slower at the crowded subtest.

8.3.8.1 Primary Analyses

Normality of Data

The frequency distributions for the mean results in each subtest suggested that the data only loosely approximated a normal distribution. A normality test was applied to: the VST data for each subtest under each condition and for both groups separately and combined; the binocular, monocular and total means; the binocular factor; and the crowding factor. None of these variables differed significantly from a normal distribution ($p > 0.05$). The p-values were all greater than 0.10, except the binocular search time in sub-test R for the combined and control groups ($p = 0.087$ and 0.096 respectively); these results support the use of regression analyses, which assume normality. During the comparative statistical analyses, however, an unusual discrepancy was observed between some of the results of parametric and non-parametric tests; non-parametric comparative statistical tests, therefore, were used.

Inter-Group Differences

The first hypothesis, that the dyslexic group would be slower at this test, was investigated by calculating the "fundamental mean search time" from the data for all subtests under both conditions. The dyslexic group was significantly slower than the control group (Mann-Whitney U test, 1-tailed, corrected for ties; p = 0.012). The differences between the groups in each subtest under each condition were tested statistically, and the results are shown in Table 8.35. In most subtests, particularly the harder ones, the dyslexic group was significantly slower than the controls. The mean search times for the binocular and monocular conditions were calculated from all the subtests; the dyslexic group was significantly slower under both conditions (Mann-Whitney U test, 1-tailed, corrected for ties; p = 0.01 for the binocular and 0.02 for the monocular condition).

condition	subtest	p-value
binocular	3	0.064
	4	0.005
	5	0.034
	R	0.003
monocular	3	0.032
	4	0.072
	5	0.051
	R	0.012

Table 8.35 Table of comparative statistics for the 2 groups in each subtest and each condition of the visual search task. The "p-value" is the 1-tailed value calculated from the Mann-Whitney U test (corrected for ties).

8.3.8.2 Secondary Analyses

Psychometric Correlates of VST Performance in The Dyslexic Group

The VST requires similar low-level sensory and motor visual function as reading. It is only in higher level linguistic processing, and the interaction of this with lower-level function (Hendricks, 1991), that these 2 tasks differ. It has been suggested that impaired perception of text (Stein and Fowler, 1984; Irlen, 1983) or eye movement abnormalities (Prechtl, 1962; Frank and Levinson, 1973) are major causes of dyslexia. The VST performance should be as severely impaired by these hypothesised deficits as reading; a comparison of Figures 8.1 and 8.7 suggests that this is not the case.

Separate and multiple regressions were carried out for the "fundamental mean search time" on the following psychometric variables: Neale rate and accuracy, coding (WISC-R), visual sequential memory (VSM), and auditory sequential memory. The VSM emerged as a major confounding variable of VST performance; poorer VSM performance was associated with slower VST results. Coding and Neale rate and accuracy also significantly interacted with VST performance, although to a lesser degree than VSM. The regression of mean search time on VSM was highly significant ($r = 0.483$; $p = 0.0014$, 1-tailed, ANOVA of partitioned sum of squares) and 23.4% of the variance in VST performance could be accounted for by the variation in VSM.

The VSM test design incorporates large symbols (Kirk et al., 1968). The perception of these is unlikely to be influenced by visual perceptual dysfunctions of the kind described by Stein (1991a) and Irlen (1983) or by abnormalities of sequential eye movements. Impaired VSM is a correlate of dyslexia (Bakker and Schroots, 1981) and it seems likely that the difference in VST performance in the 2 groups can be largely attributed to psychometric rather than optometric variables. It is uncertain, owing to the lack of detailed psychometric data for the controls, whether psychometric variables account for all the difference between the 2 groups in the VST performance. The presence of such confounding variables, however, inevitably reduces the difference between the groups' VST performance that is likely to result from a low-level visual problem; this would suggest that such problems do not play an overwhelming causative role in dyslexia.

Hulme (1981, pp. 24-25) suggested that a simulated reading task could be used to investigate visual perceptual problems in dyslexia; hence, the present results may suggest that lower-level visual problems are not major factors in dyslexia. He cited one study in which dyslexic children performed slower than controls at a visual search task; the results of this task, however, would have been confounded by motor skills since it required the subjects to underline the search item. Eakin and Douglas (1971) proposed that dyslexia was caused by defective automatisation skills; the VST requires automaticity skills, and the present data do not support his hypothesis.

Search Task Results and V/A and Refractive Error

The Spearman correlation co-efficients between the mean binocular search time and both the binocular near V/A and mean SER were calculated. The effect of V/A on performance at the search task was further investigated by examining the correlation between binocular factor and the difference between the binocular and right eye near V/As. These correlations, for each group individually and both together, are given in Table 8.36. For both groups combined the slower search times were significantly associated with worse binocular near V/A, but the significance of this relationship was not maintained for each group individually.

variables	group	correlation	
		r_s	p
mean binocular search time and bin. near V/A	both	0.228	0.02
	control	0.068	0.33
	dyslexic	0.202	0.11
mean binocular search time and mean SER	both	0.110	0.16
	control	0.019	0.45
	dyslexic	0.293	0.039
binocular factor and B-R near V/A	both	0.009	0.47
	control	-0.059	0.35
	dyslexic	0.084	0.31

Table 8.36 The correlation between 2 visual search task variables and 3 basic refractive variables. "bin. near V/A" is the binocular near visual acuity (with any usual refractive correction) in logMAR units and "B-R near V/A" is the difference between the right eye and binocular near V/As (a higher positive value represents better binocular acuity). "r_s" represents the Spearman correlation co-efficient (corrected for ties), the 1-tailed significance of which is given by the adjacent "p" value.

Relative hypermetropia was significantly correlated with slower binocular search times in the dyslexic group. Section 8.3.2.3 showed that the mean SER of the 2 groups was not significantly different, and the present findings, therefore, may suggest a reduced ability of the dyslexic group to compensate for hypermetropia. This notion was supported by the reduced accommodative amplitude, which was not related to the SER, and reduced V/A in the dyslexic group (*see* Section 8.3.8.2. The analyses in Table 8.36 also suggest that the binocular factor was not the result of differences between the right eye and binocular V/As.

Search Task Results and Vergence Dysfunction

The mean and median binocular factor in the control group were small positive numbers whilst the equivalent values in the dyslexic group were small negative numbers; the 2 groups, however, were not significantly different in this variable (Mann-Whitney U test, 1-tailed, corrected for ties; $p = 0.12$). The correlation co-efficients between the binocular factor and the results from several of the binocular vision tests were then calculated, for both groups together and individually (*see* Table 8.37). These relationships were investigated further by analysing the differences between the equivalent correlation co-efficients for the control and dyslexic groups; these approached significance for the correlations involving associated heterophoria (2-tailed $p = 0.067$) and reached significance for those involving stereopsis (2-tailed $p = 0.014$).

variables	group	correlation	
		r	p
binocular factor and vergence stabil.	both	0.410	0.0014
	control	0.299	0.052
	dyslexic	0.529	0.0018
binocular factor and abs. ass. 'phoria	both	0.168	0.14
	control	-0.003	0.98
	dyslexic	0.402	0.019
binocular factor and vergence amp.	both	-0.016*	0.89
	control	0.064*	0.68
	dyslexic	-0.226*	0.18
binocular factor and stereopsis	both	0.128	0.52
	control	-0.124	0.18
	dyslexic	0.422	0.019

Table 8.37 Correlation of binocular factor and 4 binocular vision variables. "vergence stabil." is the stability of response on the Maddox Wing test (in Δ), "abs. ass. 'phoria" is the absolute value of the near horizontal associated heterophoria, "vergence amp." is vergence amplitude, and "stereopsis" is the Titmus Test result at 80 cm. "r" represents the Spearman (Pearson when *) correlation co-efficient (corrected for ties), the 2-tailed significance of which is given by the adjacent "p" value.

A puzzling aspect of the results in Table 8.38 is that the direction of all the significant correlations are contrary to expectations; i.e., relatively improved binocular performance was significantly associated with: increasing vergence instability within the combined and dyslexic groups, increasing associated heterophoria in the dyslexic group, and worsening stereopsis within the dyslexic group. One possible explanation of these paradoxical findings is that higher degrees of binocular instability are associated with increased associated and decompensated heterophoria. Foveal suppression is a compensatory mechanism to relieve the symptoms and visual confusion that may result from decompensated heterophoria (Stidwill, 1990, p. 72). This could successfully prevent a decompensated heterophoria from interfering with binocular (compared to monocular) performance, but would have the disadvantage of impairing stereopsis. This hypothesis was investigated by calculating the Spearman correlation co-efficient between the degree of foveal suppression and the binocular factor (*see* Table 8.38).

variables	group	correlation	
		r_S	p
binocular factor and foveal suppress.	both	-0.10	0.18
	control	-0.34	0.014
	dyslexic	0.19	0.12

Table 8.38 Correlation of binocular factor and foveal suppression. "r_S" represents the Spearman correlation co-efficient (corrected for ties), the 1-tailed significance of which is given by the adjacent "p" value.

Table 8.38 shows that in the control group there was a significant tendency for increasing degrees of foveal suppression to be associated with a reduced binocular factor.

Contrastingly, and in support of the hypothesis, there was a tendency for increased foveal suppression to be associated with improved binocular performance in the dyslexic group; this, however, did not reach significance. It was noted in Section 8.3.3.6 that the foveal suppression test was prone to certain confounding variables but that these were unlikely to be relevant in the present study. These variables were, however, investigated to confirm the validity of the relationships in Table 8.38; the variables include uncorrected anisometropia and amblyopia.

The left near V/A was subtracted from the right and similarly the left acuity on the suppression test was subtracted from the right; these calculations were performed in Logmar units. The inter-ocular difference with the Mallett Unit was then subtracted from that with the letter chart, and the absolute value of the difference was calculated. The result ("relative suppression") is a value of foveal suppression when inter-ocular differences in the V/A are partialled out; this calculation, however, suffers from several practical problems. The Mallett suppression test does not possess the features of a "Bailey-Lovie type chart": there is an unequal number of letters on each line, there is not a logarithmic progression between lines, and the spacing between the lines does not appear to be related to the size of letter on the adjacent lines (Mallett, undated). The logmar values on a Bailey-Lovie design of letter chart relate to the angular subtense of the stroke widths of the letters (Bailey and Lovie, 1976). The angular subtense that is quoted for the letters on the foveal suppression chart relates to the actual size of the letters (Mallett, 1966) and these are internally illuminated in such a way that they cannot be accurately measured.

The relative suppression, despite these problems, was calculated; this resembled a normal distribution and did not differ significantly between the 2 groups (this concurs with the result in Section 8.3.3.6). When the Spearman correlation co-efficients equivalent to those in Table 8.38 were calculated, they were found to be identical in direction and similar in magnitude (both groups, $r_S = -0.183$, $p = 0.052$; control group, $r_S = -0.484$, $p = 0.0009$; dyslexic group, $r_S = 0.163$, $p = 0.16$). These results support the assumption in Section 8.3.3.6 that uncorrected anisometropia and amblyopia were not significant confounding variables in the test of foveal suppression.

It may be concluded that foveal suppression was significantly associated with worse binocular (relative to monocular) search task performance in the control group and that there was a non-significant tendency for it to be associated with better binocular performance in the dyslexic group. This finding may suggest that foveal suppression aids search task performance, possibly by compensating for binocular dysfunction, in the dyslexic group relative to the control group.

Search Task Results and Accommodative Dysfunction

The correlation co-efficients between the mean binocular search time and the binocular amplitude of accommodation are shown in Table 8.39. These analyses do not support the hypothesis, proposed in Section 8.3.8.2, that the dyslexic group's VST performance was impaired by a relative inability to accommodate to correct any hypermetropia.

variables	group	correlation	
		r_s	p
bin. search time & binocular amp. of accom.	both	-0.137	0.11
	control	-0.059	0.35
	dyslexic	0.017	0.46

Table 8.39 Correlation of mean binocular search time ("bin. search time"), in seconds, and the binocular amplitude of accommodation ("binocular amp. of accom.") in dioptres. "r_s" represents the Spearman correlation co-efficient (corrected for ties), the significance of which is given by the adjacent "p" value.

Search Task and Dunlop Test Results

The hypothesis that those subjects, particularly from the dyslexic group, with an unfixed reference eye would perform relatively worse at the binocular condition of the VST was investigated in 2 ways. Firstly, the correlation co-efficients between the binocular factor and the degree of stability of reference eye in the Dunlop Test (using the discrete interval scale) were calculated. The correlations for the groups separately and together (*see* Table 8.40) did not support the hypothesis.

variables	group	correlation	
		r_s	p
binocular factor & Dunlop test stability	both	0.074	0.26
	control	-0.065	0.34
	dyslexic	0.191	0.14

Table 8.40 Correlation of binocular factor and the stability of response in the modified Dunlop Test (using the discrete interval scale). "r_s" represents the Spearman correlation co-efficient, the 1-tailed significance of which is given by the adjacent "p" value.

The second method that was used to test this hypothesis employed Stein and Fowler's (1981) method of classifying the subjects as those with a fixed or unfixed reference eye. When the binocular factors of the "fixed" and "unfixed" sub-groups were statistically compared the results tended to support the hypothesis; this reached significance in the combined group and approached significance in the dyslexic group (*see* Table 8.41).

group	refer. eye	N	mean	SD	p
combined	fixed	24	4.5	13.3	0.033
	unfixed	53	-1.8	14.4	
control	fixed	17	4.6	13.1	0.25
	unfixed	26	0.8	13.5	
dyslexic	fixed	7	4.5	15.1	0.055
	unfixed	27	-4.3	15.1	

Table 8.41 Descriptive and comparative statistics for the binocular factor on the VST (in seconds) with respect to the stability of the referent eye ("refer. eye") on the Dunlop Test. "N" is total number and "SD" is standard deviation. The "p" values in the right hand column were calculated using the Mann-Whitney U test (1-tailed, corrected for ties).

The hypothesis that the presence of an unfixed reference eye in conjunction with vergence dysfunction in the dyslexic group would be associated with relatively poorer binocular performance at the VST was also investigated using the Stein and Fowler (1981) classification. The children with unfixed reference were sub-divided into those with normal or poor prism vergence amplitude. Comparative statistics were used to test whether the binocular factor was less in those members of the dyslexic group who had an unfixed referent eye in combination with low vergence amplitudes.

The measurement of prism vergence amplitude is influenced by several variables including: apparatus, target design, illumination, and speed of adjustment (Mallett, 1988). The control data, therefore, were used to obtain normal values for prism vergence amplitude. Table 8.18 gives the mean prism vergence amplitude for the control group as 35.1 Δ and the standard deviation as 10.7 Δ. Hence, children in the dyslexic group whose prism vergence amplitude was more than 1 standard deviation lower than the control mean (i.e., less than 24.4 Δ) were classified as having "poor" vergence amplitude. The data in Table 8.42 do not support the hypothesis that the presence of an unstable reference eye combined with binocular instability was associated with relatively impaired binocular VST performance.

group	verg. amp.	N	mean	SD	p
dyslexic with	normal	19	-5.8	15.0	0.28
unfixed referen.	poor	8	-0.8	15.9	

Table 8.42 Descriptive and comparative statistics for the binocular factor with respect to the prism vergence amplitude ("verg. amp.") (*see* text) for those members of the dyslexic group who exhibited an unfixed referent eye. "N" is total number and "SD" is standard deviation. The "p" values in the right hand column were calculated using the Mann-Whitney U test (1-tailed, corrected for ties).

Search Task Results and Pattern Glare and Transient System Function

Figure 8.7 shows that in the binocular condition both groups, but the dyslexic group to a greater degree, were slower in subtest R than in subtest 5, although in the monocular condition both groups performed relatively faster in subtest R. There would appear to be 3 possible explanations for this. Firstly, since subtest R was carried out binocularly first, there could have been an atypical practice effect with this subtest, which has a different structure to the other subtests. Secondly, subtest R has a close spacing that, unlike the other widely spaced subtests, could cause pattern glare. The effect of pattern glare may be greater when the target is viewed binocularly (Evans and Drasdo, 1991) and this could account for the slower binocular performance in this subtest. Thirdly, the random spacing and "block" size in subtest R would necessitate a far greater degree of global saccadic programming than in the other subtests. Lovegrove et al. (1986a) have suggested that a transient system deficit in dyslexia could impair saccadic programming. A transient system deficit could, therefore, be linked to the slower performance at subtest R.

The second explanation was investigated by regressing the crowding factor on the susceptibility to pattern glare, as measured in 3 ways (*see* Section 8.3.6). The results of these regressions are given in Table 8.43, and do not support this explanation.

regression of:	group	regression	
		r	p
crowding factor on integer sum experimental	both	0.022	0.86
	control	0.036	0.82
	dyslexic	0.046	0.76
crowding factor on integer difference	both	0.032	0.78
	control	0.001	0.99
	dyslexic	0.097	0.58
crowding factor on real difference	both	0.033	0.74
	control	0.005	0.98
	dyslexic	0.005	0.98

Table 8.43 Regression of crowding factor on 3 pattern glare variables. The variable column is explained in the text. "r" represents the Pearson correlation co-efficient, the significance of which is given by the adjacent "p" value (2-tailed, from ANOVA of partitioned sum of squares).

The third explanation was investigated by regressing the crowding factor on the log flicker threshold. The points did not significantly fit any regression line for the control (ANOVA, 2-tailed $p = 0.99$), dyslexic (ANOVA, 2-tailed $p = 0.64$), or combined groups (ANOVA, 2-tailed $p = 0.78$); and the correlation co-efficients for the control and dyslexic groups were not significantly different (2-tailed $p > 0.20$). To conclude, it seems likely that the faster performance in sub-test R monocularly than binocularly relative to sub-test 5 resulted from an atypical practice effect.

To ensure that a transient system deficit or pattern glare were not in some other way influencing performance on the VST, the log flicker threshold and the 3 pattern glare variables in Table 8.43 were regressed on the mean binocular search time. For the combined group, the regression of the log flicker threshold on mean binocular search time was of border-line significance ($r = 0.171$; $p = 0.080$, 1-tailed from ANOVA of partitioned sum of squares). The relationship was in the anticipated direction, the subjects who were better at detecting flicker tended to be quicker at the VST, and none of the other regressions were significant. The regressions within each group did not approach significance (1-tailed $p > 0.10$) and the correlation co-efficients did not significantly differ from one another (2-tailed $p > 0.20$).

The crowding factor was also compared in the 2 groups. It was slightly higher in the dyslexic group but this did not reach significance (Mann-Whitney U test, 1-tailed, corrected for ties; $p = 0.30$) and the difference between the correlation co-efficients of the 2 groups was not statistically significant (2-tailed $p > 0.20$).

8.3.8.3 Summary and Discussion

The dyslexic group was slightly slower than the control group at the VST, and this finding reached significance in most of the sub-tests and for the mean search times. The small size of this difference, combined with the fact that 23% of the variance in the VST performance in the dyslexic group can be accounted for by the variation in VSM, suggests that low-level visual problems do not play a major causative role in dyslexia.

Slower binocular search times were significantly associated with worse binocular near V/A, but only when both groups were combined, and the difference between binocular and monocular search times was not related to differences in V/A. Slower search times were, within the dyslexic group, significantly correlated with relative hypermetropia but were not significantly correlated with the amplitude of accommodation. The difference between the binocular and monocular search times was not significantly different between the 2 groups, and this difference was not associated with worse performance at binocular vision tests. Relatively slower binocular performance was, however, significantly correlated with an unstable referent eye; this finding reached significance in the combined group and was of border-line significance in the dyslexic group. Neither pattern glare nor a "transient system deficit" were significantly correlated with performance at the VST.

An interesting finding was that on 3 binocular vision tests, which may be measures of binocular instability, vergence dysfunction was correlated with *improved* binocular performance at the VST. This may be related to the finding that, relative to the control group, the dyslexic group demonstrated a positive correlation between the binocular factor and foveal suppression. Foveal suppression might be expected to regress binocular function towards monocular, reducing any binocular factor; and this was the case in the control group. The fact that this was not the case in the dyslexic group could be understood if the foveal suppression was successfully correcting binocular instability. The significant correlation between dissociated vergence instability and foveal suppression (*see* Section 8.3.3.9 supports this notion. If higher degrees of binocular instability in the dyslexic group were corrected by foveal suppression, but lower degrees were not, then this could explain the positive correlation between the binocular factor and some measures of vergence dysfunction.

8.3.9 Symptoms and History

In all cases a parent was present at some point in the examination and the data for this section was complete, except for family history of the 2 adopted children (*see* Section 8.3.9.1. The blind protocol was broken (i.e., the experimenter was aware, at some stage of the examination, of which group the child belonged to) for 57.3% of the subjects. There were several reasons for this, including when the author remembered the name of a child from a previous contact. During the eye examination many parents or children could not be prevented from giving information that made it clear from which group they originated. In several cases a child demonstrated difficulty in reading letters from left to right, or confused these directions (both "dyslexic" problems). For these reasons, the blind protocol was considered broken for 74.4% of the dyslexic group compared with 41.9% of the control group.

8.3.9.1 Primary Analyses

Personal Ocular History

A significantly greater proportion of the dyslexic group (79.5%) than of the control group (27.9%) had had a previous eye examination (chi-square with continuity correction; $p = 0.001$). Similarly, significantly more of the dyslexic (41.0%) than the control group (14.0%) had a history of refractive correction (chi-square with continuity correction; $p = 0.01$). None of the subjects had ever used tinted lenses, other than normal sun-glasses. Subject b20 had been recently prescribed glasses that he had not yet collected. Six members of the control group possessed spectacles that were meant to be worn in class; all of these reported wearing their glasses normally for distance and near. Eleven of the dyslexic subjects had been prescribed spectacles for use in class, 6 of these wore them for distance and near, 1 for distance only, and 4 did not regularly use their glasses.

No subjects had a history of ocular pathology; infrequent childhood bouts of non-persistent conjunctivitis were not recorded as pathology. There was a history of binocular vision problems for 2 control and 5 dyslexic children; this difference was not statistically significant (chi-square with continuity correction; $p = 0.35$). Details of the binocular vision problems were as follows:

b02	prescription since age 6 for right esotropia, long-sightedness, and amblyopia; initially patching (poor co-operation); no strabismus ever seen when Rx worn
b24	patching for "lazy eye" for 2 years at age 5, no known history of strabismus
d03	esotropia seen if tired since birth; patching at age 3-4 for 8 weeks; no glasses or other treatment
d04	"lazy eye" detected at age 4, initially prescribed spectacles, but no other treatment
d23	convergence exercises and patching prescribed at age 7, neither carried out
d35	examined at local eye hospital and given occlusion therapy, ? for unfixed Dunlop Test result
d37	eye exercises 1 year ago to help "binocular co-ordination"

Visual Symptoms

All of the control subjects and 89.7% of the dyslexic group reported that their distance vision was normally clear; this difference was not statistically significant (chi-square with continuity correction; $p = 0.10$). A transient blurring of distance vision that occurred approximately once a week was reported by 16.3% and 15.4% of the control and dyslexic groups respectively (chi-square with continuity correction; $p = 0.85$); none of the subjects reported a more frequent blurring than this. The duration of the transient distance blur did not differ significantly between the 2 groups (Mann-Whitney U test, 1-tailed; $p = 0.46$).

All members of the control group reported that their near vision was normally clear compared with 92.3% of the dyslexic group; this difference was not statistically significant (chi-square with continuity correction; $p = 0.21$). A transient blurring of near vision occurred significantly more often in the dyslexic group (Mann-Whitney U test, 1-tailed; $p = 0.024$), and the duration of this blurring was significantly longer in the dyslexic group (Mann-Whitney U test, 1-tailed; $p = 0.032$).

Episodes of diplopia were reported by 23.1% of the dyslexic and 7.0% of the control groups; this difference was of border-line significance (chi-square with continuity correction; $p = 0.081$). The rarity of this symptom precludes statistical analysis of the nature of the diplopia, but the following details were obtained:

a14	rarely, during distance vision, lasts for approx. 1 second, only when distance vision blurs
b18	approx. once every 3 days, during intermediate vision, lasts for a few seconds
a36	less than once a week, lasts for a few seconds, only when "strains eyes"
d16	once a fortnight, lasts for a few seconds
d17	rarely, lasts for a few seconds (details very vague)

d20 rare, stops when concentrates, only if tired
d22 most days, during distance vision, becomes single in few seconds, ? has occurred for as long as can remember, possibly occurs after changing fixation
d23 3 times a week, during distance or near vision, lasts for a few minutes, when tired
d24 once a fortnight, during distance vision, lasts for a few seconds
d33 once a fortnight, during near vision, lasts for a few seconds

Headache

Two subjects (b02 and d21) who only suffered headaches on the rare occasions when they did not wear their glasses were not counted as headache sufferers. Approximately equal numbers of both groups reported suffering from headaches at some time other than when ill (48.8% and 43.6% of the control and dyslexic groups respectively). The frequency of these headaches was not significantly different between the 2 groups (Mann-Whitney U test, 1-tailed; $p = 0.48$). Only 2 members of the control and 1 of the dyslexic group thought that they experienced headaches that were associated with reading.

General Health, Medication, and Allergies

The general health was stated to be other than good in only 2 cases: subject b12 who had an upper respiratory tract infection, and subject d39 who had catarrh. Some form of prescribed medication was being used by 10 of the subjects, and details of these are given below:

b06 Ventolin (salbutamol, a $beta_2$-adrenoceptor stimulant) - for asthma
b10 Trimethoprim (an anti-bacterial) - for an urinary tract infection
b12 Dithrocream (dithranol) - for eczema
a16 inhaler (details unknown) - for asthma
a23 Ventolin (salbutamol) - for asthma
b31 Triludan (terfenadine, an anti-histamine) - for hay fever (also uses eye drops and inhaler, details unknown)
b33 inhaler (details unknown)
b40 Ventolin (salbutamol) and becotide (beclomethasone dipropionate, a corticosteroid) - for asthma

d13 inhaler and steroids (details unknown) - for asthma
d16 decongestant (name unknown) - for chronic cough

There was no significant difference in the use of prescribed medication between the 2 groups (chi-square with continuity correction; $p = 0.13$). Most of the subjects who were using inhalers for asthma only used these infrequently, when required.

Bronchial asthma can be allergic (extrinsic asthma) or non-allergic (intrinsic asthma). Although an allergic trigger is thought to be more common in childhood than adult asthma, the evidence is inconclusive and in many individuals both factors are thought to play an important role (Berkow, 1982, p. 615). Gole et al. (1989) considered all cases of asthma as allergic in origin; this precedent was followed in the present study. The incidence of allergies in the 2 groups was not significantly different (Mann-Whitney U test, 1-tailed; p = 0.48). This finding was confirmed by using a simple binary nominal scale where any past history of an allergy was scored as 1, and no history as 0. A slightly greater proportion of the dyslexic group had a history of allergy (41.0%) than of the control group (32.6%), but this finding did not reach significance (chi-square with continuity correction; p = 0.57).

Family History

Data on family history were missing for 2 subjects (d05 and b21), who were adopted. Only 3 subjects had a family history of binocular vision problems (d11, b20, b24). There was a family history of migraine,by self-report, in 39.5% of the dyslexic group compared with 21.4% of the control group; this difference was not statistically significant (chi-square with continuity correction; p = 0.13). None of the dyslexic subjects reported a family history of epilepsy, compared with 11.9% of the control group; this difference was of border-line significance (chi-square with continuity correction; p = 0.083).

8.3.9.2 Secondary Analyses

For the secondary analyses, the subjects were reclassified according to their symptoms and history (the x-variables), so that the relationship of the x-variable with different optometric variables (y-variables) could be investigated for each group, and both groups combined. The y-variables were binocular vision, accommodative, or pattern glare variables. The x-variables were the presence or absence of: transient near blurring, diplopia (at any time), headaches, and allergies. The first and last of these x-variables was originally collected as a score from 1-5, and was transformed into a binary classification for the secondary analysis. In the following analyses, only p-values less than 0.10 will be quoted.

Symptomatology and Binocular Vision Variables

When both groups were combined, those subjects who reported transient near blurring had a significantly greater degree of dissociated vergence instability (Mann-Whitney U test, 1-tailed; p = 0.003). A similar finding for the control group was highly significant (Mann-Whitney U test, 1-tailed; p = 0.0003), although only 4 of these experienced some transient blurring, but did not reach significance for the dyslexic group. When the other x-variables were used, the degree of vergence instability was not significantly different in those subjects with or without the symptoms, except for the finding of border-line significance (Mann-Whitney U test, 1-tailed; p = 0.054) that those members of the control group who had a history of allergy tended to exhibit greater vergence instability.

Subjects who had reported episodes of diplopia were significantly more likely to have lower prism vergence amplitudes than those who did not experience diplopia. This was significant for both groups combined (unpaired t-test, 1-tailed; $p = 0.0007$), and for the control and dyslexic groups separately (unpaired t-test, 1-tailed; $p = 0.028$ and 0.021 respectively). No significant relationships were found between the other x-variables and the prism vergence amplitude.

Symptomatology and Amplitude of Accommodation

When both groups of subjects were combined, those children who reported a transient blurring of their near vision or diplopia were found to have significantly lower binocular amplitudes of accommodation (Mann-Whitney U test, 1-tailed; $p = 0.051$ and 0.040 respectively). Within the control group, the significance was only maintained for the transient blurring, and not for diplopia; and within the dyslexic group the significance was lost for both x-variables. No significant relationships were found using the other x-variables.

Symptomatology and Pattern Glare

There was a tendency for those children who reported transient near blur or diplopia to experience more anomalous visual effects on viewing the experimental grating. The significance values (unpaired t-test, 1-tailed) for the symptoms of transient blur and diplopia respectively were: for both groups combined 0.056 and 0.023, for the control group alone 0.22 and 0.058, and for the dyslexic group alone 0.18 and 0.021. When similar analyses were performed that were based on the difference between the number of illusions seen with the experimental and control patterns, there were no significant findings for the combined or dyslexic groups, and a border-line finding for the x-variable of diplopia in the control group (unpaired t-test, 1-tailed; $p = 0.069$). The significance of this was increased with equivalent analyses using the system of grading the severity of the illusions. For the control group the p-value became 0.052, the p-value for the combined group was now of border-line significance (0.094), although that for the dyslexic group was still not significant.

Geschwind and Behan (1982) suggested that left handedness may be associated with immune disease, headache, and learning disabilities. A possible link between this theory and pattern glare was hypothesised in Section 4.4.2.4. This was investigated by calculating, for the dyslexic group, the sum of the incidence of headaches (0 or 1), the incidence of allergies (0, 1, or 2), and the presence of left handedness (0 or 1). The

Spearman correlation co-efficients between this value and the 3 relevant pattern glare variables were calculated. The anticipated positive correlation existed, but was not significant for the absolute number of illusions seen with the experimental grating (r_S = 0.184, 1-tailed p = 0.13), and approached significance for the relative number of illusions without a grading system (r_S = 0.234, p = 0.074) and with a grading system (r_S = 0.245, p = 0.066). It may be important that, unlike previous analyses concerning pattern sensitivity, the significance of these results actually increased when the response to the control grating was taken into account.

8.3.9.3 Summary and Discussion

A significantly greater proportion of the dyslexic group had a history of primary eye-care and refractive correction. These findings could be explained by several factors: atypical parental concern (the parents of the dyslexic children had all sought a private psychological assessment); a logical investigative approach for RD; increased visual symptoms in this group; and a greater willingness of eye-care practitioners to prescribe a border-line prescription in cases of reading disability. This last explanation could also account for the relatively smaller proportion of the dyslexic group who actually wore the glasses they had been prescribed. None of the subjects had a history of ocular pathology and there was a similar incidence of previous binocular vision problems in both groups.

The presence of blurred distance vision and the incidence and duration of transient blurring of distance vision in the 2 groups was not significantly different. The presence of blurred near vision was not significantly different in the 2 groups, but the dyslexic group did report transient blurring significantly more frequently and for a significantly longer duration than the control group. Reports of diplopia were also more common in the dyslexic group (this finding was of border-line significance).

The data obtained concerning headaches, general health, medication, and allergies were similar in the 2 groups. The incidence of a family history of binocular vision problems or migraine were also similar in the groups, although there was a tendency (of border-line significance) for the dyslexic group to have *less* family history of epilepsy. It was noted in Section 7.4.10 that the incidence of migraine reported in this study was probably very conservative.

Transient blurring of near vision was associated with vergence instability and reduced amplitude of accommodation in the control group, but not in the dyslexic group. This may suggest that transient blurring in dyslexia is more likely to result from cognitive difficulties than from visual problems. Conversely, the incidence of episodes of diplopia was significantly related in both groups to a decreased prism vergence amplitude. This suggests that reduced vergence amplitude, in some cases, can lead to a transient break down of binocular vision. The infrequent nature of the episodes of diplopia, however, should be noted; this mitigates against the widespread treatment of reduced vergence amplitudes. Ball (1982, p. 126) noted that transient diplopia is experienced by a patient if a compensated heterophoria breaks down but is quickly corrected, as when some object in the environment acts to disturb fusion.

Transient blurring has been described as a symptom of binocular instability (Giles, 1960, p. 464) or decompensated heterophoria (Pickwell, 1989, pp. 30-31) and the increased incidence of transient blurring in the dyslexic group could be interpreted as supporting the suggestion in Section 8.3.3.11 of an increased incidence of binocular instability in this group. The lack of a significant correlation between these variables and vergence dysfunction, however, detracts from this hypothesis.

Transient blurring and diplopia in dyslexia has been attributed to SSS, which may be synonymous with pattern glare (*see* Section 4.4.2.4). Although there was a tendency for the subjects who experienced diplopia to be those who reported more anomalous effects on viewing a grating that could cause pattern glare, this finding lost significance for the dyslexic group when the illusions seen in a control pattern were taken into account. The present study found equivocal evidence to suggest that the incidence of headaches, allergies, and left handedness may be linked with pattern glare.

Table 8.44 summarises the results of this section, and their implications for the hypotheses proposed in Table 7.3.

	Hypothesis	Implication from Results
1	Transient blurring and doubling are more prevalent in the dyslexic group	supported
2	The presence of these symptoms is associated with the results of binocular vision & accommodative tests	supported
3	The presence of these symptoms is associated with the pattern glare test results	probably not supported
4	There is an association between pattern glare and the incidence of headaches in both groups	not supported
5	There is more history of allergies (including asthma) in the dyslexic group	not supported
6	There is an increased family history of epilepsy in the dyslexic group	not supported
7	There is a link between left handedness, repetitive headaches, history of allergies, and pattern glare in the dyslexic group.	partially supported
8	There is more history of binocular vision problems in the dyslexic group	not supported

Table 8.44 Table summarising the support for the hypotheses relating to symptoms and history.

8.4 PSYCHOMETRIC AND OPTOMETRIC VARIABLES

Some optometric variables may be correlated with the degree of reading retardation within the dyslexic group; the appropriate correlation co-efficients for the most relevant optometric variables are given in Table 8.45. The "distrib." column in Table 8.45 differentiates those variables that were or were not normally distributed or were from a binary ordinal scale; these were tested with the Pearson and Spearman correlation co-efficients and unpaired t-tests respectively. Clearly, the large number of correlations in Table 8.45 increases the risk of a Type 1 error.

optometric variable	distrib.	read. retard.		FSIQ		PIQ		VIQ	
		r	p	r	p	r	p	r	p
binocular near V/A	not normal	-0.182	-	-0.191	-	0.046	-	-0.353	0.03
mean SER	not normal	-0.036	-	-0.392	0.016	-0.415	0.01	-0.194	-
vergence amplitude	normal	0.054	-	0.284	<0.10	0.084	-	0.339	<0.05
vergence stability	not normal	0.121	-	-0.16	-	-0.132	-	-0.086	-
relative suppression	not normal	-0.389	0.016	-0.225	-	-0.207	-	-0.200	-
bin. amplit. accomm.	not normal	0.115	-	0.231	-	0.090	-	0.288	0.076
stability of refer. eye	not normal	0.340	0.044	-0.030	-	-0.111	-	0.035	-
stable/unstable	binary		-		-		-		-
PG integer sum expt.	normal	0.022	-	0.256	-	0.236	-	0.144	-
PG integer difference	normal	0.215	-	0.211	-	0.272	<0.10	0.061	-
PG real difference	normal	0.217	-	0.226	-	0.290	<0.10	0.069	-
SCSF ratio 1/12	normal	0.043	-	0.376	<0.05	0.260	-	0.355	<0.05
TCS threshold	normal	-0.182	-	-0.407	<0.02	-0.277	<0.10	-0.318	-
mean bin. search time	normal	-0.178	-	-0.294	<0.10	-0.228	-	-0.294	<0.10
recoded N freq. blur	binary		-		-		-		-

Table 8.45 Relationship between several optometric variables and 3 psychometric variables (separately). "mean SER" is the mean SER of each eye by subjective refraction, "bin." is binocular, "amp. accomm." is amplitude of accommodation (in dioptres), "stability of referent eye" is the stability of the referent eye (recorded on a discrete interval scale), "stable/unstable" is the stability of the referent eye scored using a binary ordinal scale, "PG" is pattern glare (these variables are explained in Section 8.3.6), "SCSF ratio 1/12" is the ratio of the spatial contrast sensitivity at 1 to 12 cycles/°, "TCS" is log temporal contrast sensitivity, "recoded N freq. blur" is whether or not a subject reported the symptom of near blur. "read. retard." is reading retardation (in months), "FSIQ" is full-scale IQ, "PIQ" is performance IQ, and "VIQ" is verbal IQ (all in deviation IQ points). The "distribution" column and statistics are explained in the text; for clarity 2-tailed p-values > 0.10 are recorded as "-".

Only 2 of the optometric variables in Table 8.45 were significantly correlated with the degree of reading retardation; increasingly severe reading retardation was inversely correlated with increasing degrees of foveal suppression, and a less stable referent eye was associated with better reading skills. Both these findings were contrary to expectation. The foveal suppression results may further suggest that this is a useful compensatory mechanism to overcome the relatively poor vergence amplitude and control in the dyslexic group.

The results in Table 8.45 also reveal that within the dyslexic group relative hypermetropia was associated with lower full-scale IQ; this was attributable to a significant association with performance IQ, but not verbal IQ. This finding concurs with the literature (*see* Section 2.3.3). Two of the pattern glare variables showed a tendency to be associated with lower performance IQ, but not with verbal IQ, and this did not reach significance for full-scale IQ. There was a non-significant tendency for lower verbal and performance IQs to be associated with "a transient system deficit", as measured by the temporal contrast sensitivity, and these combined to produce a significant correlation with the full-scale IQ.

Some optometric variables were significantly correlated with verbal IQ, but not with performance IQ; these may be important because they represent confounding variables that were not controlled for in the present study. The variables that showed a tendency to be correlated with lower verbal *and* full-scale IQ, but not with performance IQ, were reduced vergence amplitude, reduced spatial contrast sensitivity at 1 relative to 12 cycles/°, and slower binocular search times. Worse binocular V/A and lower binocular amplitude of accommodation were correlated with lower levels of verbal IQ, but not with the other measures of intelligence.

8.4.1 Discussion

These findings may suggest that the assumption in Section 5.4.2.3 that performance IQs are a more appropriate method of matching the groups than verbal IQs was incorrect for some of the optometric tests. There is a high correlation between WISC(R) verbal and performance scores in general (Weschler, 1974) and dyslexic (Naidoo, 1972, pp. 54-58) populations, and in 2 of the 3 optometric variables that correlated significantly with the verbal but not the performance IQ, the correlation with the performance IQ was in the appropriate direction. This suggests that, even in these cases, the performance IQ would have partially controlled for the variation in verbal IQ. Additionally, the correlation between verbal IQ and some optometric variables within the dyslexic group does not necessarily implicate verbal IQ as a confounding variable in the control group or in comparisons between the groups (*see* Section 9.2.1).

8.4.1.1 Controlling For Verbal Intelligence

Clearly, it is desirable to re-analyse some of the main study results whilst controlling for verbal intelligence. Few studies have assessed the correlation between the MHV scores and WISC(R) verbal intelligence, although one study found a high correlation (r = 0.93) between the MHV and Binet vocabulary (Raven et al., 1988b). Dunsdon and Roberts (1955) tested 2,000 children with 4 vocabulary tests and found correlations between the WISC vocabulary subtest and each of the MHV subtests ranging from 0.809 to 0.846.

Dunsdon and Roberts (1957) showed that the scores on these tests were normally distributed. Court and Raven (1982) cited a study by Fitch in 1966 in which the "CPM was found to correlate more highly with WISC verbal at lower level than at higher one"; unfortunately, no more details were given and this reference is not readily available. The (limited) evidence, therefore, suggests that it may be appropriate to match the WISC(R) verbal IQ values for the dyslexic group with the control's MHV results.

Preparation and Treatment of Data

The WISC(R) verbal IQ values were based on USA norms, and the MHV scores, therefore, were converted to percentile rankings based on USA norms (Raven, 1990a), and then converted to deviation IQ points using the table given by Raven (1990a). The descriptive statistics for the resultant verbal IQ values (*see* Table 8.46) show a significantly lower verbal IQ in the dyslexic group (unpaired t-test, 1-tailed; p = 0.0072). This concurs with the literature (e.g., Thomson and Grant, 1979; Hulme, 1981, p. 20; Stanovich, 1991).

group	mean	SD	min.	max.
control	113.6	13.0	79	135
dyslexic	106.7	12.3	80	124

Table 8.46 Summary of descriptive statistics of verbal IQ, in deviation IQ points. "SD" is standard deviation, and "min." and "max." minimum and maximum results respectively.

The reading retardation that was used to define the dyslexic group employed regression equations that link age, IQ, and reading performance and have been derived from large populations (Rutter and Yule, 1975). The psychometric data available for the control group precluded a similar technique and the present analyses used the "Schonell reading retardation" of both groups, which was calculated as the difference between the Schonell reading age and the chronological age at the time of the psychological assessment.

Each optometric variable was designated as an x-variable, the Schonell reading retardation as the y-variable, and the verbal IQ as the z-variable. The Kendall correlation co-efficients were calculated for each pair of these variables. This was repeated for all the optometric variables in Table 8.45, except for the 2 binary variables since this type of test is inappropriate for nominal or classificatory scales (Siegel, 1956, pp. 22-23). The Kendall partial rank correlation co-efficient (Siegel, 1956, pp. 213-229; Cohen and Holliday, 1983, p. 171) was calculated in the same way as described in Section 6.3.4.1.

The results of the Kendall correlations are given in Table 8.47; the correlation co-efficient between the Schonell reading retardation and the verbal IQ was -0.312 (corrected for ties, 1-tailed; $p < 0.00003$). The sampling distribution of the Kendall partial rank correlation is not known and the significance of an observed $\tau_{xy.z}$ cannot be tested (Siegel, 1956, p. 228); the distribution is, however, generally assumed to be similar to that for the normal Kendall correlation co-efficient (Armstrong, 1991). Several of the optometric variables that were significantly different in the 2 groups showed a high correlation with the Schonell reading retardation. These correlations were only slightly reduced when the effect of verbal IQ was partialled out. The correlations between the pattern glare variables and reading retardation increased slightly when verbal intelligence was controlled for. The SER was, as expected, more highly correlated with the measure of intelligence than with reading retardation, and a similar effect was demonstrated for the relative suppression, stability of reference eye, and binocular VST performance; all these variables showed an nonsignificant correlation with reading retardation by this relatively insensitive method of analysis.

optometric variable	read. retard.		VIQ		partial
	τ_{xy}	p	τ_{xz}	p	$\tau_{xy.z}$
binocular near V/A	0.196	0.009	-0.137	0.068	0.163
mean SER	0.018	-	-0.110	-	-0.017
vergence amplitude	-0.070	-	0.073	-	-0.050
vergence stability	0.131	0.084	0.029	-	0.015
relative suppression	0.001	-	-0.123	-	-0.040
bin. amplit. accomm.	-0.219	0.0036	0.121	-	-0.192
stability of refer. eye	-0.119	-	0.186	0.015	-0.065
PG integer sum expt.	0.082	-	0.123	-	0.128
PG integer difference	0.010	-	0.170	0.024	0.067
PG real difference	0.020	-	0.167	0.026	0.077
SCSF ratio 1/12	-0.204	0.0068	0.110	-	-0.180
TCS threshold	0.330	<0.00001	-0.107	-	0.314
mean bin. search time	0.079	-	-0.126	0.10	0.042

Table 8.47 Kendall correlation and partial correlation co-efficients between several optometric variables and 2 psychometric variables (separately). For key, *see* Table 8.45.

An interesting result in Table 8.47 is that the vergence amplitude was not significantly correlated with the degree of reading retardation, although the vergence amplitude and verbal IQ were significantly lower in the dyslexic group. The reason for this is illustrated in Figure 8.8; although the mean vergence amplitude was lower in the dyslexic group, the relationship between the vergence amplitude and degree of reading retardation within each group was very different. In the control group better reading performance was associated with reduced vergence amplitude, whereas no such relationship existed in the dyslexic group.

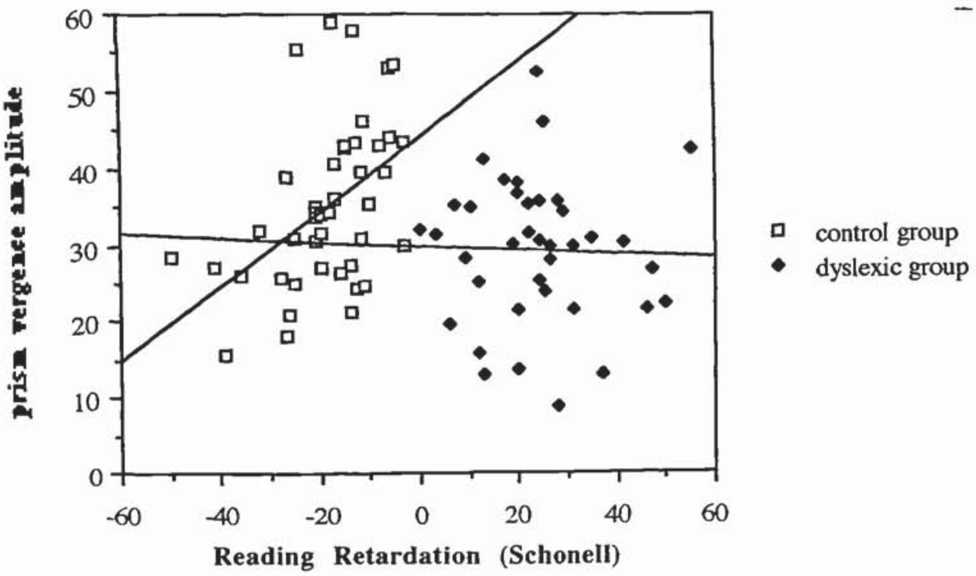

Figure 8.8 Scatterplot of prism vergence amplitude (in Δ) v. Schonell reading retardation (in months). Negative values of reading retardation represent advancement in reading. The data for both subject groups are plotted on the same figure; the regression lines for each group (separately) are drawn, the near horizontal line is for the dyslexic group.

The effect of verbal intelligence on the relationships in Figure 8.8 was investigated by a multiple regression, for each group separately, with vergence amplitude as the y-variable and Schonell reading retardation and verbal IQ as the x-variables. In the control group, the vergence amplitude was significantly associated with the reading retardation ($p = 0.0021$), but not with the verbal IQ ($p = 0.70$). The regression was significant ($p = 0.0061$), with both variables accounting for 22.5% of the variation in vergence amplitude. In the dyslexic group, the vergence amplitude was not significantly associated with the reading retardation ($p = 0.40$), but was significantly linked with the verbal IQ ($p = 0.027$). The whole regression did not reach significance ($p = 0.083$), with both variables accounting for 13.3% of the variation in vergence amplitude. When these regressions were repeated with the additional x-variable of age this had little effect on the above relationships. Age did not significantly interact with with reading retardation or verbal IQ in either group. These findings suggest that the interaction between verbal IQ, reading retardation, and vergence amplitude is quite different in the 2 groups. This may be one reason why several of the optometric variables that were significantly different in the 2 groups were not significantly correlated with the Schonell reading retardation in the combined groups. Other explanations include the disadvantages of the Schonell reading retardation, which was based on a graded word test in which several members of the control group scored over the test ceiling of 12 years 6 months; and the weaknesses of non-parametric correlational statistics of a bi-modal distribution.

8.4.2 Summary and Discussion

Within the dyslexic group, some optometric variables were significantly correlated with performance IQ, but not with verbal IQ; the most significant of these, as expected, was the mean SER. Other optometric variables were significantly correlated with verbal IQ but not with performance IQ; these included V/A, accommodative amplitude, vergence amplitude, relative spatial contrast sensitivity, and VST performance.

Further analyses were carried out to investigate the correlation between the key optometric variables whilst controlling for, as far as possible, the effect of verbal IQ. This analysis reduced the magnitude of the correlation between the Schonell reading retardation and 4 of the optometric variables: SER, relative suppression, stability of reference eye, and binocular VST performance. Although all of these variables were significantly different, by comparative statistics, in the 2 groups they were not significantly correlated with the degree of Schonell reading retardation in the combined groups, either before or after the effect of verbal IQ had been partialled out. This may be explained by the disadvantages of using the Schonell reading retardation and the weaknesses of non-parametric correlational statistics of a bi-modal distribution. This last point was investigated further by studying the relationship between verbal IQ, Schonell reading retardation, and vergence amplitude in each group. The interaction between these variables was quite different in the 2 groups; this may suggest that different factors were involved in the interplay between optometric and psychometric variables in the 2 groups.

It was concluded from the review chapters that research on the visual aspects of dyslexia should control from the effect of IQ. The findings of this section suggest that more work is needed to investigate the interaction of cognitive factors with the relationship between optometric variables and dyslexia. The present analyses were limited by the psychometric data that were available for the control group but would seem to indicate that verbal intelligence, although a relevant factor, is unlikely to have a major effect on the significance of the findings in this chapter.

8.5 General Conclusions

The main study results are reviewed in Section 9.1. Table 8.48 relates these results to the main general hypotheses outlined in Section 5.3.1.

hypothesis	results
Hypermetropia is present more often and to a greater degree in the dyslexic sample.	not supported
Binocular dysfunction is present more often in the dyslexic sample.	supported
Accommodative dysfunction is present more often in the dyslexic sample.	supported
A fixed reference eye is less well-established in the dyslexic sample.	border-line
Pattern glare is more prevalent in the dyslexic sample.	not supported
A defect of the transient visual system is present in the dyslexic sample.	supported
There is a link between a transient deficit and binocular and accommodative dysfunction.	supported
Optometric deficits in dyslexia impair performance at a simulated reading task.	border-line
Optometric deficits in dyslexia are associated with increased symptoms of visual disturbances and asthenopia.	border-line

Table 8.48 Summary of main study results in terms of the general hypotheses in Section 5.3.1. "Border-line" describes cases where the data did not provide a wholly consistent pattern of statistical significance.

CHAPTER 9

CONCLUSIONS

9.1 REVIEW OF MAIN STUDY RESULTS

The near and, to a lesser extent, the distance V/A were significantly worse in the dyslexic group, although the refractive error in the 2 groups was similar. The dyslexic group demonstrated significantly lower vergence amplitudes than the control group and this may have resulted in binocular instability and foveal suppression. The low vergence amplitudes were significantly correlated with reduced accommodative amplitudes in the dyslexic group. The amplitude of accommodation was significantly lower in the dyslexic group, but was not significantly correlated with the V/A or refractive error. There was a non-significant tendency for the dyslexic group to exhibit less stable ocular dominance with the modified Dunlop Test, and this result was not related to the vergence dysfunction. Pattern glare did not seem to be a correlate of dyslexia in the present sample, although the results of the test for pattern glare seemed to be confounded by increased suggestibility in the dyslexic group. The dyslexic group performed significantly worse than the controls at both tests that were designed to measure transient system function, although the results of these were only loosely correlated. In the dyslexic group this "transient system deficit" was associated with decreased vergence and accommodative amplitudes and with a *reduced* manifestation of pattern glare.

In most measures of VST performance the dyslexic group was significantly slower than the control group, although this slight difference was partly attributable to psychometric variables. This may suggest that visual factors do not play a major causative role in dyslexia. There was a border-line tendency for slower search times to be associated with reduced V/A and relative hypermetropia, but they were not significantly correlated with accommodative dysfunction. The difference between monocular and binocular search times was similar in the 2 groups. This difference showed a tendency to be correlated with an unstable referent eye but was not related to binocular dysfunction. The latter finding may result from foveal suppression compensating for vergence dysfunction in the dyslexic group.

The dyslexic group reported significantly more transient blurring and showed a tendency to report more diplopia than the control group. These findings, however, were not linked to accommodative and vergence dysfunction, or to pattern glare. In both groups the reports of (rare) transient diplopia were linked to reduced vergence amplitudes. The presence of a history of headaches and a family history of migraine or epilepsy was not significantly different in the 2 groups, but there was a finding of border-line significance to support a link between pattern glare and the incidence of headaches, allergies, and left handedness.

9.2 Discussion

9.2.1 Attention and "Effort to See"

Kruger (1985) found that during reading there was, on average, a small increase in accommodation (0.10 D) with cognitive demand ($p < 0.01$). There was a large inter-subject variation; in some individuals the accommodation changed very significantly (0.50-2.50 D) with cognitive demand. This effect was not related to the refractive error and did not appear to influence the subjective clarity of the target. This study, however, used large targets (equivalent to 6/24) that might reduce subjective reports of blur.

Francis et al. (1989) measured the vergence and accommodative response when subjects were instructed either to actively and carefully look at a target or to passively look in the direction of the target and relax. The vergence and accommodative responses were good for the "concentrate" condition but were significantly reduced towards the resting point of these oculomotor systems for the "relaxed" condition. The relationship between the vergence and accommodative response was unaffected.

The effect of mental effort on accommodation was reviewed and studied by Winn et al. (1991). Accommodation normally operates under closed-loop conditions when optical factors play an important role. Other, non-optical, factors such as proximity, motivation, mental activity, and imagery also play a role in the control of accommodation. These can be studied under open-looped conditions when image quality is independent of changes in accommodative state and optical factors cease to be of major importance. Under these conditions accommodation normally regresses to its resting or tonic level at approximately 1.00 D. Winn et al. (1991) investigated accommodative response in normal adults under open- and closed-loop conditions for 3 different tasks: a *passive* task when subjects read letters to themselves; a *stimulus-dependent* task (SDT) when subjects were instructed to respond only when the letter "e" appeared in one of a series of presentations; and a *stimulus-independent* task (SIT) when subjects mentally counted backwards in sevens whilst viewing the target. Their results showed that the tonic component of accommodation could be modified significantly when an impression of proximity was evoked by mental imagery. This occurred either under SDT or SIT conditions, and the difference between these conditions was less apparent under closed-loop conditions.

Hendricks (1991) found that when children read meaningful text (at a fixed distance) they made more vergence eye movements than when they read meaningless text. This difference reached significance in a dyslexic sample, but not in a control group.

Francis et al.'s (1989) implication that a lack of "effort to see" may cause vergence and accommodation to regress towards their resting point whilst leaving the AC/A ratio unaffected may suggest a vergence corollary to the research on accommodation by Winn et al. (1991). Duane (1991) noted that attention deficit-hyperactivity disorder and disorders of vigilance were unusually common in dyslexia and he described a study (unpublished) that used pupillometry to confirm an increased incidence of "daytime non-alertness" in dyslexia. Hendricks' (1991) results may suggest that cognitive demand can have an atypical influence on the vergence control of dyslexic populations.

The present research showed an increased tendency for the dyslexic group to regress towards the resting point of the accommodative and vergence systems. It is possible, therefore, that some of the optometric test results that were significantly different in the 2 groups reflect, at least in part, a "psychological factor" that is a correlate of dyslexia. This may be more closely related to verbal than performance IQ (*see* Section 8.4). This hypothesis is supported by the DT results, which suggested that subjects responses may seem less reliable in a dyslexic population than in a control population that was matched for intelligence. Further, the pattern glare results showed the dyslexic group to be more "suggestible". The hypothesis that a psychological or attentional factor could account for some of the optometric correlates of dyslexia will now be examined in more detail.

Hynd and Semrud-Clikeman (1989) described reports suggesting that learning disabilities may reflect a right hemispheric syndrome marked by emotional lability, social imperception, and poor interpersonal insight. Richardson and Stein (1991) noted that dyslexia and schizotypy had the following features in common: shared genetic predisposition, more left/mixed handers, more males than females, soft neurological signs, abnormal hemispheric specialisation, unusual sensory processing (transient system deficits), attentional disorders, abnormal linguistic function, and creative/divergent thinking. They concluded that dyslexia and schizotypy were associated and that, in both conditions, abnormal hemispheric specialisation and atypical sensory processing gave rise to an unusual cognitive style. It is possible that the "unusual cognitive style" was related to the attentional disorders and that these were the origin of some of the abnormal responses in the other tests.

The observation of abnormal pursuit eye movements in the main study was supported by the literature (*see* Section 2.5). Kowler (1989) showed that smooth pursuit eye movements were driven by a signal that combined the present with the expected target motion. The expected motion was based on a genuine cognitive prediction and this could provide a cognitive explanation for this finding in the main study.

Slightly reduced V/A emerged as a correlate of dyslexia in the main study, although the high spatial frequency contrast sensitivity sensitivity function was not significantly different in the 2 groups. Atkinson (1991) noted that the control of a shift of visual attention was an important factor in the development of saccadic and pursuit eye movements. She described the "visual crowding" paradigm, which investigated the result when visual attention to one object was degraded or masked by surrounding objects. She briefly presented a study that had found an enhanced crowding effect in dyslexia. Her groups were not matched for intelligence and this may account for her results. An alternative explanation, of impaired allocation of visual attention, cannot, however, be ruled out. The V/A in the present research was measured with morphoscopic (line) targets and a crowding effect could, therefore, explain the worse V/A in the dyslexic group.

In the main study prism vergence tests the subjects were unaware of the nature of the test or interpretation of their response. They were not instructed to make any mental effort to keep the targets single; the only stimulus to alter vergence was the preconscious detection of retinal disparity. During measurement of the NPC the subjects were asked to try and keep the target clear and, in addition to retinal disparity, also received proximal and blur-induced stimuli. Motivational effects might have been expected, therefore, to have a greater effect on NPC results than on prism vergences, although only the latter variable was significantly different in the 2 groups.

In the test of dissociated vergence stability the subjects did not know whether their answer would be interpreted as "good" or "poor". It is possible that the dyslexic group were more critical observers, but if this were the case they might have been expected also to report increased dissociated and associated heterophoria. Similarly, if the reduced amplitude of accommodation in the dyslexic group was attributable to motivational factors, it might be expected that they would also have demonstrated a more remote NPC, since this test constitutes a similar task.

The test for flicker threshold represents a difficult task and may be susceptible to criterion errors (Burbeck, 1981). It may be argued, however, that the spatial contrast sensitivity function testing controlled for criterion errors. It seems unlikely that criterion differences would reduce the dyslexic group's contrast sensitivity at low spatial frequencies without impairing their sensitivity at high spatial frequencies. This argument is weakened, slightly, by the significant correlation between verbal, but not performance, IQ and relative low spatial frequency contrast sensitivity loss in the dyslexic group. This finding may be particularly relevant since most previous work on the transient system deficit in dyslexia has only controlled for performance IQ (*see* Table 5.2).

It is concluded that psychological factors, such as attention, are unlikely to account for the significant findings in the present research. The possibility that a factor, such as a "reduced effort to see", exists cannot be ruled out, and it may be related to measures of attention. Neither can the present research completely exclude the possibility that such a factor confounds some optometric test results, including slower VST performance, and is associated with low verbal IQ and reading retardation. Until now, it has been advocated that research in this area should control for some measure of intelligence (Pierce, 1977; Bishop, 1989). It is suggested that other factors, particularly relating to attention, should be controlled for in future work (*see* Section 9.3).

9.2.2 The Link Between Motor and Sensory Visual Dysfunction

9.2.2.1 The Feedback Loop Hypothesis

Introduction

The present research has, for the first time, experimentally linked the visual processing (transient) deficit with vergence and accommodative dysfunction in dyslexia. It is important to consider if this is a causal relationship, and this will now be discussed. Vergence and accommodation are likely to be negative feedback systems (Carroll, 1982) where errors in accommodation or vergence are calculated from the retinal images to initiate any corrective motor signals. One way in which a transient visual system deficit could be directly linked to binocular or accommodative dysfunction is if the transient system atypically predominates in the sensory pathway of this feedback loop. The evidence for this hypothesis will now be considered.

Stimulus Characteristics

Some research links binocular vision (Lu and Fender, 1972) and specifically stereopsis (Yang and Blake, 1990) with sustained channels, although Merigan (1991) noted that stereopsis could be mediated by the M or P pathway depending on the spatio-temporal content of the stimuli.

Mathews and Kruger (1989) measured the accommodative response as a function of contrast and suggested from their results that accommodation might operate primarily through magnocellular-type pathways. Neary (1989) found that the accommodative response was influenced by flicker, both below and above flicker fusion. She suggested that neurones in the midbrain, which have a much higher critical flicker frequency than cortical neurones, may be involved in the control of accommodation. Iwasaki and Kurimoto (1987) found that eyestrain whilst working on a VDU screen was related to changes in accommodative oscillation in the range 0 to 1.5 Hz. Winn et al. (1990), however, demonstrated that high frequency accommodative oscillations (1.0 to 2.1 Hz) were the result of arterial pulse. Flitcroft's (1991) study also may be invalidated by a failure to consider the effect of arterial pulse.

Switkes et al. (1990) found that subjects could not accommodate to isoluminant red-green gratings. An appealing explanation for these results is that the magnocellular pathway, which has been described as "colour-blind" (Zrenner et al., 1990), is involved in the extraction of information for accommodation. However, these authors dismissed this hypothesis since it is the high spatial frequency-sensitive parvo cells that will have their inputs most affected by a defocused retinal image. Matthews and Kruger (1990) noted that isoluminant targets were not comparable with the heterochromatic nature of visible light. This view was supported by Stone et al. (1990) who found a severe disruption of accommodation when longitudinal chromatic aberration was reversed and by Kruger et al. (1991) who criticised the use of static techniques.

The Afferent Pathway

Some neurophysiological evidence has suggested that sustained ganglion cells were critically affected by defocus (Ikeda and Wright, 1972). One of the visual association areas, the middle temporal region (MT), has been implicated in the analysis of movement (Wurtz et al., 1990; Lennie et al., 1990) and, at a higher level of function, the medial superior temporal region has been linked to eye movements (Wurtz et al., 1990). Although these areas have been associated with the magnocellular pathway (Zeki and Shipp, 1988; Lennie et al., 1990), the work of Wurtz et al. (1990) relates to pursuit, not vergence, eye movements.

The Neural Control of Vergence and Accommodation

Marr and Poggio (1979) suggested that sensory fusion occurred between corresponding spatial frequency channels from the 2 eyes for disparity values of the order of the channel resolution. Channels that were sensitive to low spatial frequencies, which they supposed to be transient channels, were thought to control vergence, thus causing finer channels to come into correspondence.

The near response, or near triad, describes the 3 oculomotor responses during near vision: accommodation, vergence, and changes in pupil size. Semmlow and Hung (1983) concluded that the exact nature of the stimulus to near triad motor responses, primarily blur, primarily disparity, or a combination of the 2, was still not known, although the evidence suggested that disparity driven signals were paramount.

Hung and Ciuffreda (1988) presented evidence for dual-mode behaviour in the human accommodation system. Their findings were consistent with a recent unifying theory of oculomotor control in which the various oculomotor sub-systems (version and vergence eye movements and accommodation) have fast and slow components. The fast component exhibited pre-programming, whilst the slow component showed continuous feedback control. This theory was supported by Wick and Bedell (1989) who found that rapid vergence innervation occurred during saccades and that disparity stimuli could initiate independent rapid and slow vergence responses.

Stein (1991a) stated that information about the rate and direction of movements of images across the retina was projected via the magnocellular pathway to the posterior parietal cortex (PPC), where they were associated with eye movement signals. This association was said to be essential for precise spatial localisation, and he believed that this was achieved through directing attention to particular targets; no more details of this theory were given. He noted that the right PPC was specialised for this function and dyslexic children were said to show symptoms that were very similar, but milder, to those of patients with right PPC lesions. These symptoms were unstable binocular control, reduced stereoacuity and a less accurate sense of visual direction, particularly in the left hemifield. Stein (1991a) hypothesised that the transient system of many dyslexic children failed to develop properly; this led to impaired vergence control, which fed back to prevent normal maturation of the transient system.

The Efferent Pathway

Leigh and Zee (1983, p. 138) stated that the higher pathways responsible for vergence eye movements were unknown. Goldberg and Segraves (1990) noted that the frontal eye field (an area of the frontal lobe) was involved in the production of conjugate, particularly saccadic eye movements, although the precise nature of this involvement or of any connections between the striate cortex and the frontal eye field was unclear. The fact that vergence and saccadic eye movements are often used in combination to place objects on the fovea (Leigh and Zee, 1983, p. 138) may support the notion that they share at least some part of the same pathway.

Gamlin (1991) used physiological techniques on 2 Rhesus monkeys to show that the cerebellum was involved in the control of vergence and accommodative eye movements. Leigh and Zee (1983, p. 130) noted that the ocular motor neurons in the medial rectus division of the oculomotor nucleus discharged for all types of eye movements, both conjugate and disjunctive and that no neurons had been identified that were predominantly or exclusively concerned with vergence movements.

Conclusion

Some evidence suggests that the transient system does not exclusively control vergence and accommodation. It is not possible at this stage, however, to determine whether the transient system is paramount in this control mechanism. The possibility that vergence and accommodative dysfunction in dyslexia are the motor corollary of a (sensory) transient system deficit cannot be ruled out at the present time.

9.2.2.2 The Degraded Iconic Image Hypothesis

A transient system deficit may cause a superimposition of the input from successive fixations (*see* Section 2.7.1.4) and Lovegrove et al. (1990) suggested that this could result in inconsistent information about the spatial arrangement of letters when reading (Lovegrove et al., 1990). Stein and Fowler (1984) hypothesised that dyslexia could be caused by poor visuomotor control owing to the perceptual problem of not knowing where the eyes are pointing whilst reading. Stein (1991a) thought that this poor sense of visual direction resulted from a lesion in the right posterior parietal cortex. An alternative explanation is that a superimposition of subsequent images in the visual icon owing to a transient system deficit results in poor (unstable) binocular localisation. Both of these hypotheses might predict impaired skills at scanning and, hence, the relatively small difference in the VST performance of the 2 groups in the present research does not support these hypotheses. A confused iconic image may represent a generalised impairment of the sensory link in the feedback loop for the control of accommodation and vergence. This could, therefore, account for the decreased vergence stability and amplitude in the main study. The "degraded iconic image hypothesis" proposes, therefore, that the role of the transient system in interfering with the feedback loop controlling accommodation and vergence is an indirect one.

9.2.2.3 The Compensation Hypothesis

This hypothesis suggests that accommodative dysfunction is an adaptation to compensate for a transient system deficit. Williams et al. (1987) found that image blurring normalised the visual processing of disabled readers, supposedly through re-establishing the temporal precedence of the transient system. It is possible, although speculative, that dyslexic children with a transient system deficit could adapt to this by defocusing their accommodative system to re-establishing the temporal precedence of their transient visual system. Two features of the main study data appear to support this hypothesis: binocular instability can be caused by accommodative anomalies (*see* Section 8.3.3.11 and Section 8.3.4.5), and the resultant blurring could account for the reduced V/As (*see* Section 8.3.2.1).

This hypothesis, however, seems untenable for the following reasons. Firstly, poor V/A is *not* a particularly common finding in dyslexia (*see* Section 2.3.1). Secondly, the amplitude of accommodation was not significantly correlated with V/A in the main study dyslexic group. Thirdly, if a subject had adapted to keep a target out of focus then it might be expected that accommodative lag would be the measure of accommodation that was most affected. Whilst one study did find this to be the case (Poynter et al., 1982), this was not found in the present research. Indeed, it is hard to see why accommodative amplitude should be reduced by this hypothesis.

9.2.2.4 Diabetes Mellitus

Mantyjarvl and Nousiainen (1988) found a reduced amplitude of accommodation in diabetic children who were otherwise visually normal. Similar populations have been shown to demonstrate impaired motion perception at very low contrast (Shirao et al., 1991), an abnormal spatial contrast sensitivity function (Dhanesha, 1991), and impaired flicker detection (Dhanesha, 1991). These results are of incidental interest and it is unclear at the present time whether they are correlated with one another or are in any way likely to be analogous to findings in dyslexic children. Indeed, Mantyjarvl and Nousiainen (1988) suggested that the low amplitude of accommodation in their diabetic children resulted from changes in the crystalline lens, or toxic changes in the ciliary muscle.

9.2.2.5 Conclusions

The present research has experimentally demonstrated a link between a transient system deficit and accommodative and vergence dysfunction in dyslexia. Two feasible hypotheses have been proposed to account for this link. One of these hypotheses proposes that the transient system plays a direct and major part in the afferent pathway of the feedback loop controlling accommodation and vergence. The other proposes that a transient deficit indirectly interferes with the control mechanism by impairing spatial localisation. More work is needed to test these hypotheses.

9.2.3 Clinical Implications

Helveston (1987) summarised the viewpoint of the American Academy of Ophthalmology on the role of visual factors in dyslexia:

> "Occasionally, a reading disability may stem from a visual disorder or muscle imbalance, in which spectacles or eye muscle surgery or exercises may be of some value. Any ocular abnormality detected in a learning-disabled child should be treated according to the child's needs and according to standard principles of treatment."

The present research broadly supports this conclusion. Several areas of optometric function have been identified in which dyslexic children tend to perform worse than controls and these may cause symptoms of asthenopia (Cohen et al., 1988). It seems likely, therefore, that the need for eyecare and appropriate treatment is somewhat greater than usual in the population of children with a RD. This research, however, does not suggest that these optometric problems are major causes of the RD, and certainly does not support the use of therapeutic measures other than when indicated by conventional clinical criteria.

9.3 Implications and Suggestions for Future Work

9.3.1 General Considerations

Several attempts have been made to classify dyslexia into sub-types (*see* Section 1.6) and this has been supported by recent electrophysiological studies (Flynn and Deering, 1989). Most classifications include a "visuo-spatial" group (Doehring et al., 1981, pp. 36-40), although Lovegrove et al. (1986a) reported that this category did not necessarily include subjects with a transient system deficit. Further research could investigate the relationship between visual deficits and dyslexic sub-groups.

An important implication of the present research is that future work should investigate further the psychometric correlates of visual factors in dyslexia. Certain WISC(R) subtests (coding, digit span, mazes, and mental arithmetic) have been combined to provide a distractability factor (Vance and Singer, 1979), and this could be used to investigate the effect of attention on the optometric results.

Dyslexia is sometimes associated with dysgraphia and this may be a sign of an underlying visual defect (Husain, 1986; Snowling, 1990). Dysgraphia could be caused by other problems, such as poor motor co-ordination, but it may be interesting for future studies to investigate whether dysgraphia is more common in those dyslexic children with a visual defect.

9.3.2 Specific Areas For Further Investigation

9.3.2.1 Basic Refractive Parameters

Further investigation of the incidence of refractive errors in dyslexia seems unwarranted. Near V/A in dyslexia could be investigated further, particularly using more sensitive V/A charts. Atkinson's (1991) finding of an increased crowding effect in dyslexia should be investigated when intelligence is controlled for. Pascal's (1991) experimental pardigm is recommended for such a study and it also would be interesting to investigate the interaction between contrast and the crowding effect (Kothe and Regan, 1990) in dyslexic children. The near-normal VST performance of most dyslexic children in the main study, however, suggests that the crowding effect is unlikely to be a major problem in dyslexia.

9.3.2.2 Binocular Vision and Orthoptics

The NPC test suffers from a ceiling effect and may also be confounded by reduced accommodative amplitude. Alternative methods of measuring vergence amplitudes are likely to be of more use in future work. The vergence instability that was detected with the Maddox Wing was large enough to be measured objectively with conventional eye movement recording techniques; such research should control for the reading objective and test-type (Hendricks, 1991).

The fixation disparity curve is obtained by measuring the size of the fixation disparity for various degrees of forced vergence (Stidwill, 1990, pp. 75-77). There are several types of fixation disparity curve and these can be used to determine how well the heterophoria is compensated (Pickwell, 1989, p. 41). When a prism is placed before an eye the induced change in heterophoria or fixation disparity gradually reduces with time; this is "prism adaptation" (North et al., 1990). Adaptive disorders of accommodation and vergence may underlie some binocular disorders (Schor and Horner, 1989), and prism adaptation may determine the type of fixation disparity curve (Schor, 1983). These techniques could be used to investigate further the vergence dysfunction in dyslexia and may reveal information about vergence control mechanisms (Schor, 1983).

9.3.2.3 Accommodation

Accommodation can be continuously and reliably recorded (Pugh and Winn, 1988) whilst the subject fixates a target whose movement can be controlled to provide various step or ramp accommodative stimuli (Phillips et al., 1991). This type of apparatus can also be modified to simultaneously monitor pupil and eye movements (Okuyama et al., 1990), and can be combined with a Badal lens system to vary the optical vergence (distance) of a target without changing its spatial frequency or luminance (Phillips et al., 1991). A paradigm similar to that of Winn et al. (1991) (*see* Section 9.2.1) could firmly establish the role of mental effort and imagery in the accommodative response in dyslexia.

This experiment could be extended to measure the vergence response. The apparatus that was used by Schor and Horner (1989) was able to change the accommodative stimulus by increments of 0.02 D whilst recording vergence eye movements and accommodation to within 0.5 minutes of arc and 0.1 D respectively. The importance of future work on vergence and accommodative function in dyslexia is increased by the fact that deficits in these systems can result in symptoms and are amenable to training (Cooper et al., 1987; Reading, 1988).

9.3.2.4 The Dunlop Test

The Dunlop Test is strongly influenced by subject intelligence (*see* Section 3.3) and even when this was controlled for in the main study the test results still seemed to be influenced by the reliability of the subject's response. It seems unlikely that further research with this test would make a useful contribution to knowledge of visual aspects of dyslexia.

9.3.2.5 Stereopsis as an Investigative Technique

Reading (1983, pp. 173-191) stated that the measurement of stereo-acuity can be used to detect anomalies of V/A, refraction, accommodation, and binocular function. The present research does not support this contention. This may be because clinical tests of stereopsis allow continuous viewing; the subject is able to give a correct response if a clear stereoscopic percept is obtained at any instant during the unrestricted exposure time. This may fail to detect unstable perceptual or oculomotor anomalies. These problems should, however, reduce the probability of a subject demonstrating accurate stereopsis for short duration targets.

Future work could investigate this hypothesis using the following paradigm. A subject binocularly views a target (e.g., a word or a circle) that is instantaneously replaced for a brief period (e.g., 0.5 s) by an identical target but with a dot above or below. The dot should be either at the same distance as the word or optically displaced closer or further away. A forced choice multiple presentation design with varying stereoscopic disparities could be employed. It is possible that this type of test could be developed to screen for visual problems, particularly those that the present study has identified in dyslexia.

9.3.2.6 Tinted Lenses

The results of the main study suggest that the test for pattern glare that has been successfully used with adults (Wilkins et al., 1984) should not be used to investigate dyslexic children without a condition to control against increased suggestibility. The control condition in the main study prevented a false positive finding, but could have resulted in a false negative. There is clearly a need for a specially designed pattern glare test for children and such a test is under development (Wilkins , 1990 and 1991a, b).

Evans et al. (1991) reported a placebo-controlled blind paradigm for investigating the interaction between pattern glare, performance at a simulated reading task, and the use of tinted lenses. A pilot study using adults confirmed the suitability of this paradigm and suggested that tinted lenses and overlays may be linked to pattern glare in *good* readers. Future research could use this method to compare RD children with controls; the main study findings indicate that the flicker sensitivity should also be assessed in such a study. If pattern glare is found to be a factor in dyslexia, then the possibility that this is caused by cerebro-cytoarchitectonic abnormalities (Geschwind and Galaburda, 1985) could be investigated using hemifield tests for pattern glare (Evans and Drasdo, 1991). Wilkins' (1991b) colorimeter and carefully designed trial lenses facilitate the rigorous evaluation of the tinted lens therapy for learning disabilities. This system seems particularly well suited to the investigation of individual idiosyncrasies in the choice of tint. Wilkins and Thomson (1991) suggested that colour memory could be used, with or without the colorimeter, to investigate the tinted lens therapy in dyslexia.

Research has recently (since the main study commenced) suggested that the use of tinted lenses in dyslexia may be linked to low vergence amplitudes (Holland et al., 1991) and that their mode of action may be a compensatory one to re-establish the temporal precedence of the transient visual system (Solman et al., 1991; Williams, 1991a).

Neither of these studies looked for a transient system deficit in their sample, and more work is needed to assess the interaction between these variables.

9.3.2.7 Parallel Visual Processing

Three paradigms have been used to measure transient system function in the RD (Lovegrove et al., 1986a). The main study was the first research to assess more than 1 of these paradigms on the same sample of children and found that the results of these tests were only loosely correlated. Future research could investigate the validity of the transient deficit hypothesis by using all three measures on the same sample. A high priority for future research must be the link between oculomotor functions and the results of "tests of the transient system"; it would be interesting to investigate this in other, non-dyslexic, populations with accommodative and/or vergence dysfunction.

9.3.2.8 Miscellaneous

The main study found abnormal pursuit eye movements in some dyslexic children and this supports some other workers' observations (e.g., Frank and Levinson, 1973). Hartje (1972) pointed out that only saccadic eye movements were used during reading. Abnormal pursuit eye movements, however, have been shown to cause fixation instability during reading (Prechtl and Stemmer, 1962), possibly owing to a failure to correct drifts during fixation. It would be interesting to investigate this further, since pursuit eye movements may be mediated through magnocellular pathways (Zeki and Shipp, 1988; Wurtz et al., 1990; Breitmeyer, 1991) and abnormal pursuit eye movements in dyslexia have been attributed to central nervous system damage (Prechtl and Stemmer, 1962). Further, it has been suggested that eye movements could be used for the early objective diagnosis of dyslexia (Pavlidis, 1981a).

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APPENDIX 1

PILOT STUDY RAW DATA

subject	PN	AK	MW	LS	JG	TA	CB	CW	LK	RB
retin. SER	0.75	0.75	1.25	1.25	0.75	0.37	1.00	0.00	0.75	0.87
subjective SER	0.25	0.50	0.25	0.75	0.50	0.00	0.25	0.00	0.37	0.44
binoc. D. V/A	0.89	0.89	0.89	0.67	0.78	1.07	0.89	0.78	1.07	1.13
binoc. N. V/A	0.67	nd	nd	nd	1.00	1.00	0.89	0.67	1.00	1.00
acc. lag	nd	1.12	1.50	0.00	1.25	1.25	1.37	0.75	1.25	1.62
amp acc (binoc)	4.00	19.00	19.00	4.00	9.00	19.00	20.00	13.00	15.00	5.50
amp acc (worst)	3.50	15.00	7.00	4.00	10.00	14.00	15.00	10.50	14.00	6.00
NPC (large)	18.00	5.00	4.50	18.00	11.00	4.50	4.50	7.00	8.00	8.00
recovery	1.00	0.00	0.00	0.00	2.00	0.00	0.00	0.50	2.00	1.00
NPC (small)	nd	5.50	5.00	21.00	10.00	4.50	5.00	8.50	8.00	8.00
recovery	nd	0.00	0.00	nd	0.00	0.00	0.00	1.00	3.00	0.00
cover test	3.00	2.00	1.00	3.00	4.00	0.00	0.00	2.00	0.00	0.00
dissoc. ph. (Hz)	6.00	-1.00	2.00	2.00	4.00	-1.00	0.00	2.00	2.00	8.00
dissoc. ph. (Vt)	0.00	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
assoc. ph. (Hz)	2.00	1.00	1.00	0.00	2.00	1.00	0.00	0.50	0.00	4.00
assoc. ph. (Vt)	0.00	0.00	0.00	0.50	0.00	0.00	0.00	0.00	0.00	0.00
base in blurr	1.00	10.00	8.00	2.00	8.00	14.00	6.00	8.00	7.00	4.00
base in break	2.00	12.00	10.00	4.00	20.00	26.00	10.00	13.00	15.00	12.00
base in recov.	1.00	4.00	2.00	2.00	2.00	2.00	4.00	2.00	9.00	5.00
base out blurr	4.00	12.00	nd	2.00	nd	nd	30.00	16.00	22.00	nd
base out break	6.00	20.00	8.00	3.00	22.00	18.00	30.00	18.00	30.00	16.00
base out recov.	2.00	6.00	2.00	1.50	0.00	6.00	0.00	6.00	0.00	2.00
AC/A	2.00	1.00	1.00	2.50	2.00	1.00	1.00	1.00	1.00	0.00
stereopsis	20.00	30.00	40.00	40.00	200.0	30.00	40.00	20.00	30.00	70.00
Dunlop/synopt.	6.00	7.00	6.00	8.00	5.00	7.00	8.00	9.00	6.00	7.00
Dunlop/Mallett	6.00	9.00	7.00	5.00	5.00	7.00	6.00	5.00	5.00	7.00
pattern glare	5.72	5.72	5.72	7.15	5.72	2.86	10.00	2.86	7.15	7.15

Table A1.1 Raw data for each subject (identified by initials along top row) in the pilot study. The abbreviations are as follows: "retin." = retinoscopy; "binoc." = binocular; "D" = distance; "N" = near; "acc." = accommodative; "amp." = amplitude; "dissoc." = dissociated; "ph." = heterophoria; "Hz" = horizontal; "Vt" = vertical; "assoc." = associated; "recov." = recovery; and "synopt." = synoptophore.

APPENDIX 2
DESIGN, CONSTRUCTION, AND CALIBRATION OF FLICKER APPARATUS

DESIGN

Introduction

A mains-operated flicker generating unit (FGU) was used. This had previously been designed to make a light source flicker at a range of amplitudes and frequencies to plot the De Lange curves of patients suffering from retro-bulbar neuritis (Wright, 1983). The instrument was modified to provide an additional, constant, current supply.

These outputs from the FGU were connected via 1 m of wiring to a flicker eyepiece (FE). This was constructed by the author so that it would fit into a standard optometric spectacle trial frame. The constant output from the FGU illuminated 8 LEDs, providing the background illumination, and the sinusoidal output illuminated 1 central LED to provide the flickering stimulus. Both outputs were trimmed with fixed resistors so that their maximum current corresponded with that specified for the LEDs (*see* Table A2.1). The current from each source also could be adjusted by potentiometers and these were set before any experimentation started so that, when the central LED was flickering at zero amplitude and maximum frequency, the luminance of the field appeared uniform.

Construction of Flicker Eyepiece (FE)

The central, flickering, light source was a "LED indicator Fresnel lens" (RS Components Ltd., Northants. NN17 9RS; stock number 576-349) and the surround (background) light sources were "sub-miniature LEDs" (same supplier; stock number 587-721). Their specifications are given in Table A2.1.

technical specification	centre	surround
I_f maximum (mA)	30	80
I_f typical (mA)	20	40
Power maximum (mW)	120	225
V_f at I_f typical (V)	2.3	2.5
intensity at I_f typical (mcd)	1.5	4.5
colour	green	green
peak wavelength (nm)	565	565

Table A2.1 Technical specifications of LEDs used in the FE "I_f" is feed current and "V_f" the feed voltage.

The construction of the FE is schematically illustrated in Figure A2.1. The 8 surround LEDs were, contrary to theoretical objections, connected in parallel. They were soldered to a ring of printed circuit board that was supported by the power leads from the lens holder. The lens was a CR39 aspheric lens of focal length 11.5 mm. A solid piece of perspex was turned on a lathe so that it was the same diameter as the trial lens rim, had a hole in the centre to take the lens, and was shaped underneath so as to act as a lid to the perspex cup (Figure A2.2). This was fastened in the trial lens rim so that the cup could be held in a trial frame.

The perspex cup that formed the body of the FE was carefully turned on a lathe to produce a ridge on the inside, at a distance of 11.5 mm from the lens. A metal plate was inserted that had been cut to fit firmly against this ridge (Figures A2.2 and A2.3). A circular hole had been drilled in the centre of the plate that, after the edge had been smoothed, had a diameter of 3.5 mm. When viewed through the lens, this "artificial pupil" represented a field of 12 °.

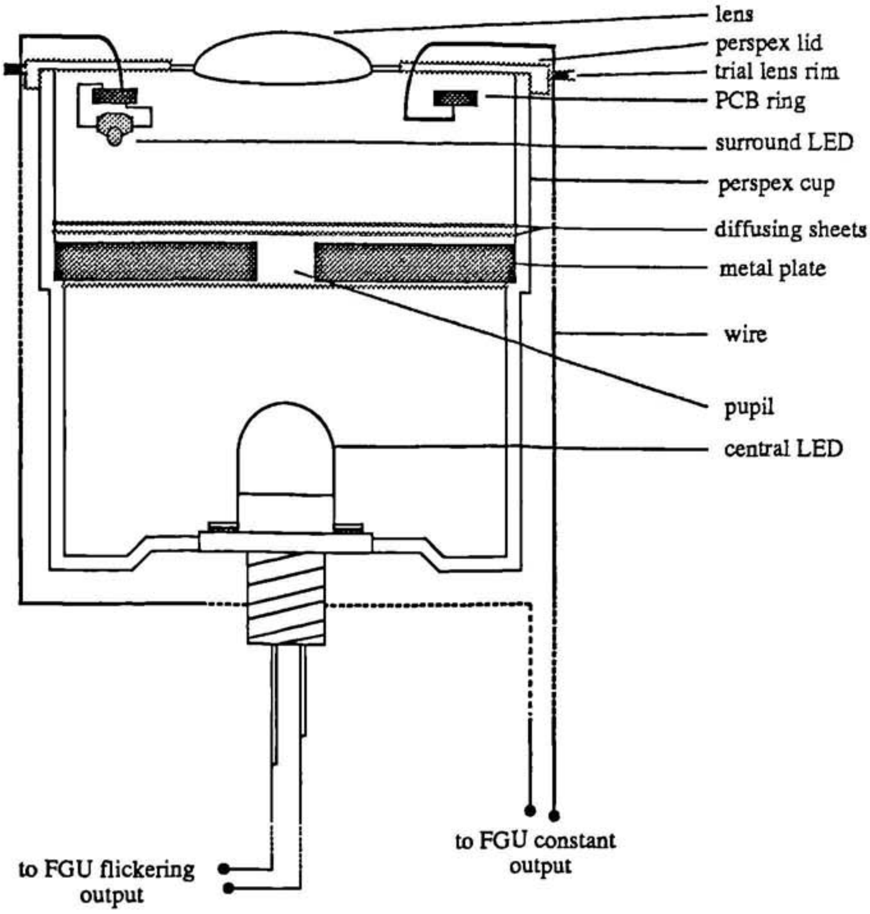

Figure A2.1 Cross-sectional diagram of flicker eyepiece (approximately to scale). "PCB" is printed circuit board.

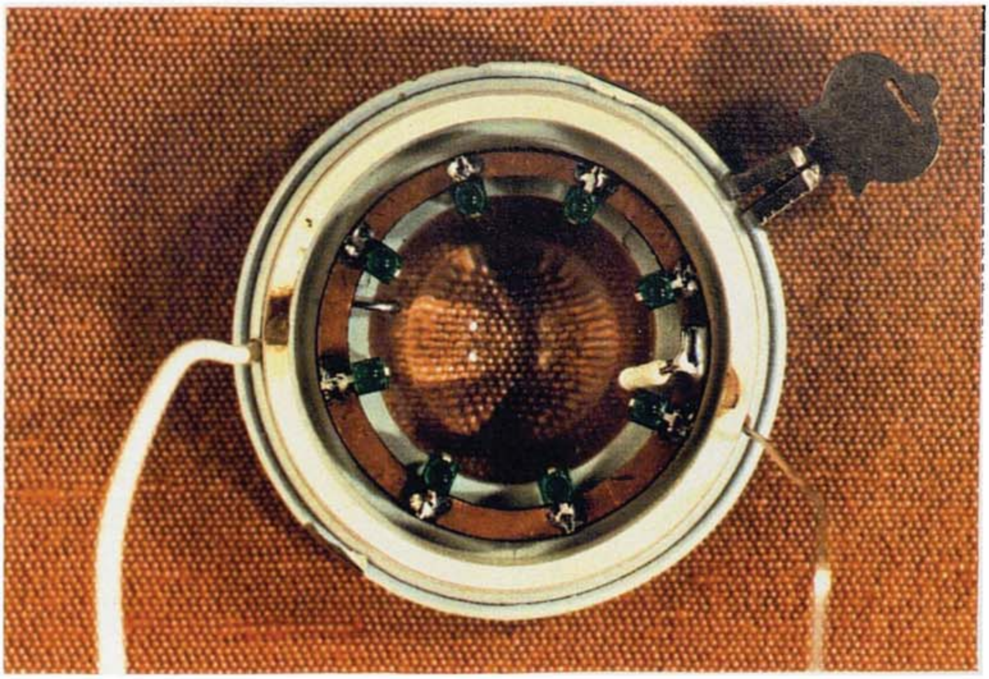

Figure A2.2 Colour print of the "lid" of the flicker eyepiece, viewed from underneath, i.e., looking directly towards where the subject's eye would be. The trial lens rim can be seen, as can the surround LEDs soldered onto the printed circuit board, which is suspended by leads from the lens mount.

Figure A2.3 Colour print of an angled view of the FE "cup", without the "lid" in place. The metal disc with artificial pupil and central (flickering) LED can be identified. This photograph was taken before the FE was sprayed and the diffusing sheets were added.

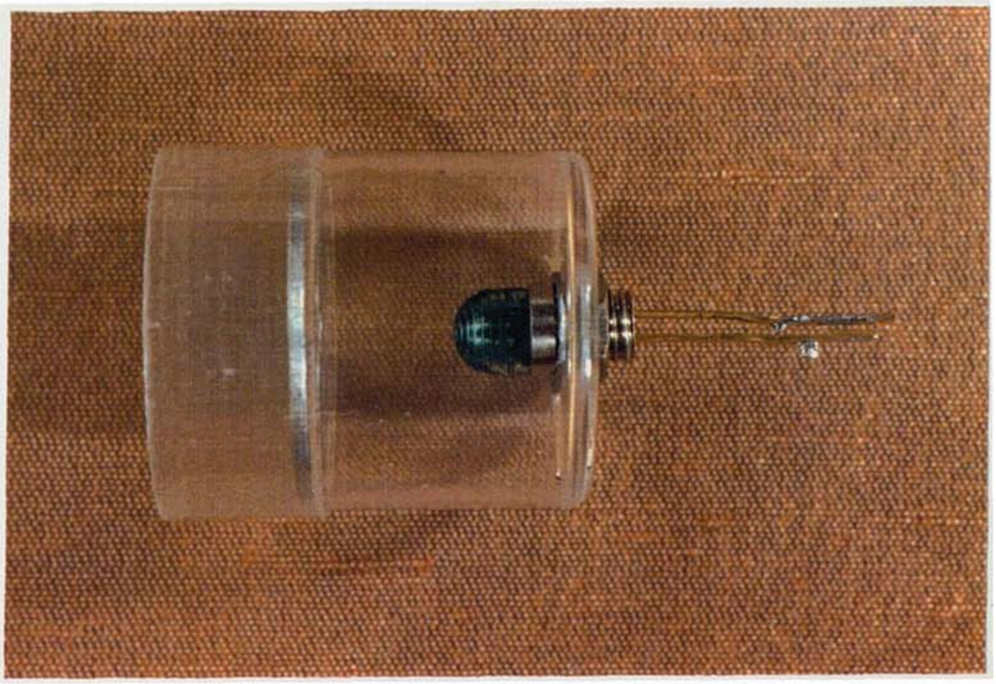

Figure A2.4 Colour print of a side view of the FE "cup", without the "lid" in place. The same description applies as for Figure A2.3.

The inside of the cup was sprayed, without the LEDs and lens in place, with several coats of white paint. A thin sheet of diffusing perspex was placed underneath the artificial iris and 2 layers were placed on top of it. These made the light sources appear homogeneous, except for any flickering, and the border between the centre and surround appear invisible. A hole had been drilled in the bottom of the cup to take the flicker LED and this was inserted and secured.

Calibration

The calibration of the flicker unit is summarised below.

1. A modified camera was initially used in which the film had been replaced by a photocell that was connected to an oscilloscope. The linearity of this camera photometer was confirmed by arranging the camera on an optical bench, in a darkened room, when it was aimed into the flicker unit eyepiece and was focussed in the plane of the anterior diffusing sheet. Only the background LEDs were illuminated and 2 readings were taken, directly and through a 1.0 neutral density (ND) filter. The oscilloscope reading was attenuated by a factor of 10, confirming that the photometer was linear.

2. The room lights were turned out and the camera photometer was re-aligned on the FE. The FE surround was extinguished, and the centre was illuminated, flickering at 10 Hz. At this low level of illuminance, the photometer integrated the flicker so that no waveform was visible. When the amplitude of the flicker was varied throughout its range the oscilloscope reading did not change, confirming that the mean luminous intensity was independant of the amplitude of flicker.

3. The flicker unit was replaced by a highly reflecting surface and **incandescent background room lighting** was adjusted until the oscilloscope reading was the same as when the FE had been present. The camera photometer was replaced with a calibrated spot photometer and the luminance of the surface was measured as 1.20 cdm^{-2}. A similar procedure revealed that the luminance of the surround (alone) was 7.4 cdm^{-2}.

To Measure the Flicker Amplitude

4. The FE, with only the centre illuminated, was aligned on an optical bench with the probe of an IDT photometer that was connected directly to an oscilloscope. The oscilloscope readings (in mV) to the top and bottom of the sinusoidal waveform were obtained for various amplitude settings. In this way, a graph of setting v. mV was obtained.

5. The FE was then replaced by a uniform light source that could be dimmed with a potentiometer. Two 1.0 ND filters were placed in front of the photocell and this was connected to an oscilloscope. An highly reflecting surface was placed adjacent to the photocell and the calibrated spot photometer was aimed at this surface. The potentiometer was varied so that several readings were taken with the photocell and oscilloscope (in mV) with corresponding spot photometer readings (cdm^{-2}).

6. The absolute peaks and troughs of the sinusoidal luminance waveform with the background on were now calculated by adding 7.40 cdm^{-2} (*see* 3. above) to the values obtained in 5. This resulted in the graph on the left in Figure A2.5.

7. The data in Figure A2.5 (left-hand graph) were substituted into the Michelson (1891) Contrast formula:

$$\frac{L_{max} - L_{min}}{L_{max} + L_{min}}$$

A graph for converting the instrument setting into Michelson contrast was then plotted (*see* Figure A2.5, right hand graph).

8. The readings at low contrast levels were difficult and were not feasible below a contrast of approximatley 0.005. This is unfortunate, since the threshold of most subjects were slightly lower than this. The graph on the right in Figure A2.5 demonstrates that the relationship between the instrument setting and Michelson contrast was linear. Additionally, the FGU was designed so that a setting of 0 must correspond with a contrast of 0. A graph was plotted, therefore, with 2 points corresponding to a setting of 100 and 0.

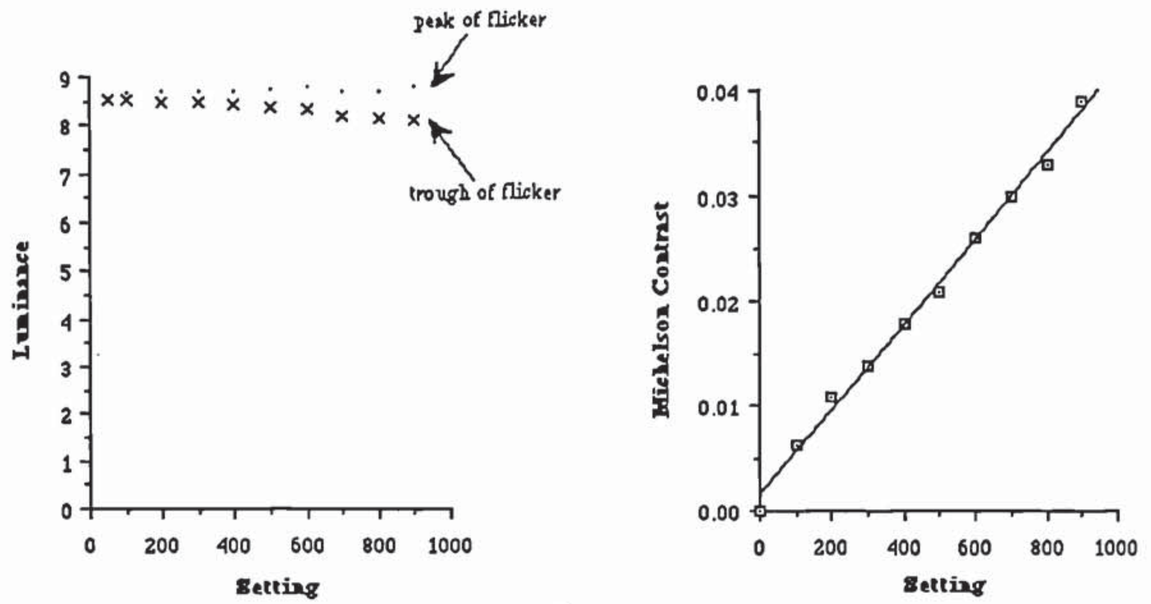

Figure A2.5 Graphs of luminance (cdm^{-2}) of the peak and trough of the flicker waveform v. instrument setting and. Michelson contrast v. instrument setting. The best fitting line has been drawn through the points on the right hand graph.

The regression line was calculated and is illustrated in Figure A2.6. This regression formula was used prior to the statistical analysis to directly convert the instrument setting to a contrast reading. It is conceivable that some non-linearity was present in the very lowest values, although extrapolation was the only feasible method of obtaining satisfactory estimates for these points.

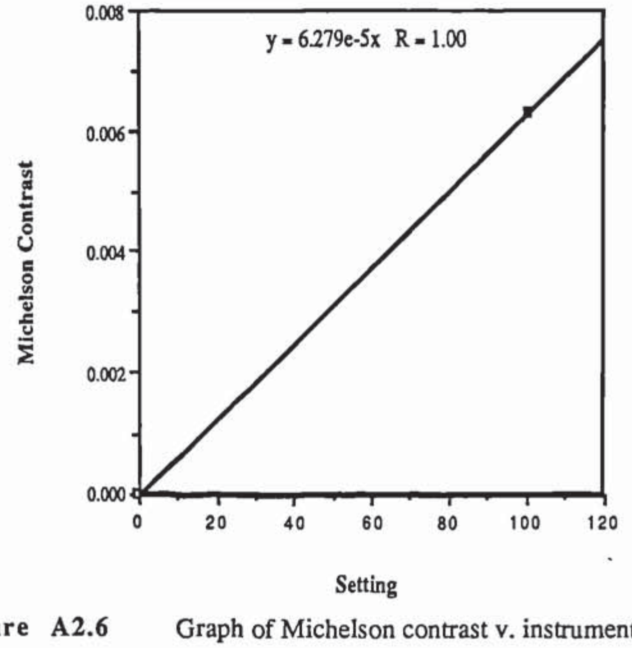

Figure A2.6 Graph of Michelson contrast v. instrument setting.

APPENDIX 3
VISUAL SEARCH TASK SUBTESTS USED IN MAIN STUDY

The visual search task subtests that were used in the main study are illustrated in Figures A3.1-4. These are all 80% of the actual size that was used.

628	542	383	942	608	135
009	329	201	434	975	466
367	124	457	976	632	882
616	896	575	497	894	402
596	861	153	578	885	150
909	662	252	992	359	956
244	158	548	724	246	884

Figure A3.1 Visual search task subtest 3 that was used in the main study.

8992	2818	4238	4061	2835	7557
0553	7611	8865	9652	8495	5824
9101	9467	5660	7297	5322	4948
2529	4906	4861	4466	5282	8933
1507	4246	5490	6487	1726	3996

Figure A3.2 Visual search task subtest 4 that was used in the main study.

58216	26027	85168	58493	42470	64644
31529	94106	44785	57242	69178	26883
89231	98789	39467	50639	05595	47966
50550	36442	12352	99254	08269	06828

Figure A3.3 Visual search task subtest 5 that was used in the main study.

62854 498864 564 89 3520 53 290 0143 4 97516 636248
44529 7663 318 26 1579697 2497 808 48259 652 114
357 688515 0709662 292 152 35295644 88489 0912 0

Figure A3.4 Visual search task subtest R that was used in the main study.

APPENDIX 4

MAIN STUDY RAW DATA

ref.	sex	dob	date optom.	date psych.	FSIQ	PIQ	VIQ	RA	SA
d01	1	7/4/79	9/1/91	31/8/90	106	122	94	106	98
d02	1	9/2/80	2/1/91	29/6/90	121	123	115	118	112
d03	1	14/4/82	31/10/90	24/9/90	98	98	98	79	74
d04	0	14/8/81	5/12/90	15/10/90	128	126	124	97	102
d05	1	20/10/78	5/10/90	18/6/90	100	104	97	99	95
d06	0	13/5/80	5/12/90	31/10/90	105	109	102	95	92
d07	0	13/11/80	16/11/90	18/6/90	105	115	97	89	80
d08	1	6/6/79	24/10/90	31/8/90	123	124	117	107	102
d09	1	12/9/81	23/10/90	31/8/90	129	133	119	102	84
d10	1	1/8/81	31/10/90	19/9/90	95	104	88	82	69
d11	1	15/12/78	31/10/90	29/1/90	102	93	111	110	104
d12	1	12/2/81	23/10/90	29/8/90	113	106	117	98	96
d13	1	8/4/82	5/10/90	27/7/90	112	114	108	81	77
d14	1	8/12/82	15/8/90	6/6/90	120	112	122	87	74
d15	1	12/2/79	16/7/90	23/3/90	99	104	95	87	80
d16	1	26/4/80	13/8/90	2/7/90	109	106	109	113	85
d17	1	1/10/80	14/8/90	18/5/90	115	118	103	91	76
d18	1	11/7/82	9/8/90	14/3/90	90	104	80	72	71
d19	1	30/9/80	8/8/90	13/7/90	102	96	107	82	76
d20	0	21/1/79	7/8/90	25/5/90	127	115	114	116	121
d21	1	12/10/79	29/6/90	10/1/90	101	100	103	99	88
d22	1	20/11/78	28/6/90	2/4/90	105	102	108	99	103
d23	1	3/7/79	24/10/90	7/9/90	115	123	106	109	102
d24	0	3/5/82	28/1/91	7/12/90	103	112	96	91	94
d25	0	30/12/80	30/1/91	10/12/90	105	106	103	99	96
d26	1	21/1/80	29/1/91	30/11/90	115	106	119	110	108
d27	0	14/1/80	30/11/90	2/11/90	93	105	85	80	79
d28	1	18/6/82	3/12/90	19/10/90	122	115	123	100	92
d29	1	29/5/79	16/7/90	23/3/90	133	135	124	117	92
d30	1	29/12/81	29/11/90	12/10/90	121	126	113	89	80
d31	1	27/3/78	18/6/90	5/2/90	125	126	119	118	114
d32	0	17/11/80	24/7/90	5/4/90	92	96	90	84	73
d33	1	10/1/79	5/10/90	24/7/90	101	102	101	92	84
d34	1	5/5/78	23/8/90	16/7/90	112	105	117	91	92
d35	1	5/3/81	14/1/91	29/10/90	98	87	108	92	92
d36	0	8/7/78	29/11/90	28/9/90	102	98	106	121	135
d37	1	14/2/83	30/11/90	7/9/90	115	115	112	81	74
d38	1	3/9/81	31/10/90	3/9/90	107	121	95	86	79
d39	1	1/7/82	30/11/90	10/10/90	113	115	109	87	80

Table A4.1 Raw data for general and psychometric details of dyslexic group (continued in Table A4.2. The abbreviations are as follows: "ref." = subject reference number; "dob" = date of birth; "date optom." = date of optometric examination; "date psych." = date of psychological assessment; "FSIQ" = full-scale IQ; "PIQ" = performance IQ; "VIQ" = verbal IQ; "RA" = Schonell reading age (months); and "SA" = Vernon spelling age. Sex is coded as 1 for male.

ref.	Neale acc.	Neale comp.	Neale rate	WISC coding	VSM	ASM
d01	111	131	105	13	22	7
d02	112	130	114	10	23	8
d03	80	80	78	6	13	7
d04	97	134	95	16	21	6
d05	106	114	93	10	19	9
d06	90	106	79	9	14	9
d07	93	90	97	12	18	5
d08	107	133	96	11	20	8
d09	108	130	99	13	16	nd
d10	82	78	89	7	11	2
d11	113	144	102	6	20	10
d12	98	113	83	7	18	9
d13	86	98	78	5	17	6
d14	86	98	95	5	17	12
d15	95	94	86	9	18	8
d16	109	128	107	8	12	9
d17	95	101	93	8	16	10
d18	68	75	78	7	15	6
d19	84	90	91	3	18	9
d20	111	145	103	7	25	8
d21	102	109	95	6	17	5
d22	107	130	97	5	17	10
d23	111	133	96	18	24	nd
d24	84	96	95	14	18	9
d25	93	113	97	10	24	7
d26	107	134	76	8	nd	8
d27	66	65	78	9	25	6
d28	97	101	120	13	20	6
d29	108	131	97	9	20	nd
d30	95	101	95	7	20	8
d31	124	150	104	13	27	nd
d32	85	90	85	9	24	8
d33	94	98	90	5	18	9
d34	99	113	99	8	23	7
d35	81	76	66	6	16	9
d36	120	140	112	7	22	nd
d37	82	81	81	8	14	7
d38	91	98	87	10	20	8
d39	90	101	96	10	15	7

Table A4.2 Raw data for general details and psychometric tests of dyslexic group in main study (continued from Table A4.03. The abbreviations, in addition to those already defined, are as follows: "acc." = accuracy; "comp." = comprehension; and "nd" = no data.

ref.	sex	dob	date optom.	date psych.	PIQ	VIQ	RA	SA
b01	1	1/1/79	17/7/90	4/4/90	120	114	148	156
b02	1	19/4/80	6/8/90	4/4/90	127	92	147	160
a03	1	27/3/82	14/12/90	9/7/90	98.5	112	113	100
b04	0	11/7/81	26/7/90	4/4/90	122	104	126	130
a05	1	18/12/78	15/10/90	9/7/90	108	115	150	156
b06	0	11/7/80	18/7/90	4/4/90	110	135	137	145
a07	0	18/9/80	21/11/90	9/7/90	113	124	142	158
a08	1	1/10/79	22/11/90	9/7/90	122	128	150	175
a09	1	6/9/81	16/11/90	9/7/90	135	135	147	158
b10	1	29/12/81	7/8/90	4/4/90	105	117	138	136
b11	1	7/4/79	18/7/90	4/4/90	97	111	137	136
b12	1	2/2/81	31/7/90	4/4/90	111	114	142	134
a13	1	11/6/82	19/10/90	9/7/90	115	115	114	142
a14	1	1/7/82	19/10/90	9/7/90	113	119	124	114
a15	1	24/3/79	9/10/90	9/7/90	109	111	150	170
a16	1	7/4/80	17/10/90	9/7/90	106.5	124	144	142
a17	1	17/12/80	11/10/90	9/7/90	117	116	142	158
b18	1	14/11/82	30/8/90	4/4/90	105	109	114	106
b19	1	4/9/80	9/8/90	4/4/90	94	79	118	136
b20	0	7/6/79	19/7/90	4/4/90	115	123	150	186
b21	1	23/6/79	14/8/90	4/4/90	102	114	150	192
b22	1	15/5/79	17/7/90	4/4/90	106	93	138	178
a23	1	18/2/79	16/11/90	9/7/90	120	116	150	170
b24	0	11/2/82	30/7/90	4/4/90	112	109	104	102
b25	0	19/11/80	30/7/90	4/4/90	109	114	138	138
a26	1	25/3/80	2/1/91	9/7/90	109	116	135	145
b27	0	12/7/79	23/8/90	4/4/90	106	102	144	156
a28	1	9/6/82	2/1/91	9/7/90	120	128	147	125
b29	1	30/9/78	1/8/90	4/4/90	97	110	150	170
a30	1	5/11/78	15/11/90	9/7/90	122.5	118	150	145
b31	1	28/12/78	16/7/90	4/4/90	88	101	148	190
a32	1	17/1/79	6/12/90	9/7/90	127	135	150	170
b33	1	17/4/79	24/7/90	4/4/90	126	98	148	178
b34	1	24/9/79	17/7/90	4/4/90	112	135	146	145
b35	1	6/2/80	8/8/90	4/4/90	94.5	107	125	118
a36	1	15/3/80	4/10/90	9/7/90	135	125	150	154
b37	1	19/1/81	6/8/90	4/4/90	96	117	126	140
b38	1	1/6/81	25/7/90	4/4/90	114.5	110	123	134
a39	1	11/3/82	4/1/91	9/7/90	108.5	120	136	123
b40	1	2/4/82	13/8/90	4/4/90	92	90	113	128
b41	0	8/7/82	7/8/90	4/4/90	113	91	111	108
b42	0	21/10/78	9/8/90	4/4/90	120	106	144	175
b43	0	12/4/80	26/7/90	4/4/90	105	131	128	145

Table A4.3 Raw data for general details and psychometric tests of control group in main study. The abbreviations are the same as those in Table A4.2. The PIQ and VIQ were the Ravens matrices and Mill Hill vocabulary scores, respectively, converted to deviation IQ points.

ref.	BD V/A	best M. D - BD	BN V/A	RN V/A	LN V/A	R ret SER	L ret SER	R sub SER	L sub SER	R sub cyl	L sub cyl	aniso-met.	mean corr V/A
b01	-0.1	0.02	0.08	0.14	0.22	1.25	1.75	0.75	0.88	0	0.25	0.13	-0.1
d01	0.04	0.18	0.08	0.18	0.18	2.00	2.38	1.00	1.00	0.5	0.5	0.00	0.05
b02	-0.1	0	-0.06	0.3	0	3.50	0.50	2.50	-0.25	0	0.25	2.75	0.19
d02	-0.1	-0.02	-0.04	0.1	0.1	0.75	1.00	0.25	0.25	0	0	0.00	-0.1
a03	-0.08	-0.02	-0.04	0.06	0.08	0.88	0.88	0.62	0.37	0.5	0	0.25	-0.055
d03	-0.06	0.06	0.12	0.8	0.12	0.75	1.00	0.25	0.50	0	0	0.25	0.24
b04	-0.1	0.02	-0.04	0.12	0	1.25	0.88	0.50	0.25	0	0	0.25	-0.07
d04	-0.06	0.14	0.18	0.2	0.2	0.50	0.50	-0.38	0.13	1.25	0.25	0.50	0.13
a05	-0.1	0	-0.06	-0.08	-0.08	1.25	1.25	0.63	0.50	0.25	0	0.13	-0.1
d05	-0.1	0	-0.04	-0.02	0.26	1.00	0.75	0.13	0.25	0.25	0.5	0.13	-0.1
b06	-0.1	0.12	0.06	0.14	0.12	1.25	1.00	0.25	0.13	0.5	0.25	0.13	-0.1
d06	-0.1	0.08	0.08	0.16	0.12	0.25	1.13	-0.63	1.00	1.75	0.5	1.63	-0.1
a07	0.14	0.34	-0.04	0.16	0.16	-0.88	-0.63	-0.87	-0.62	0	0	0.25	-0.04
d07	-0.1	0.02	-0.06	-0.06	0.16	0.75	0.75	0.00	0.00	0	0	0.00	-0.07
a08	-0.08	0	-0.04	0.06	-0.02	1.50	0.75	1.75	0.75	0	0	1.00	-0.01
d08	-0.04	0.02	-0.02	0.02	0.06	0.50	0.75	0.25	0.38	0.5	0.25	0.13	-0.04
a09	-0.1	0.02	-0.08	-0.04	-0.06	0.00	0.50	-0.50	0.25	0.25	0	0.75	-0.08
d09	0.2	0	0.5	0.4	0.52	0.50	0.25	-0.25	0.25	0	0	0.50	0.09
b10	-0.06	0.04	-0.04	0	0.08	5.00	6.38	4.75	5.13	1	0.25	0.38	-0.04
d10	0.04	0.16	0.22	0.5	0.58	1.00	0.75	0.38	0.63	0.25	0.25	0.25	0.06
b11	-0.08	0.08	0.24	0.32	0.24	1.75	2.13	1.38	1.62	0.75	0.5	0.25	-0.1
d11	-0.06	0	-0.04	0.1	0.1	0.50	0.75	0.25	0.50	0	0	0.25	-0.09
b12	0.02	0	0.06	0.08	0.22	-4.50	-4.00	-4.00	-4.00	0	0	0.00	-0.01
d12	-0.02	0	0	0.04	0.08	1.00	1.00	0.50	0.50	0.5	0.5	0.00	-0.05
a13	-0.1	0.14	0.04	0.04	0.1	1.25	0.75	0.50	0.50	0.5	0	0.00	-0.01
d13	0.02	0	-0.02	0.1	0	1.13	1.00	0.50	0.50	0.5	0	0.00	-0.06
a14	0.04	0.04	0.22	0.34	0.24	1.00	0.38	0.38	0.12	0.75	1	0.26	0.1
d14	-0.04	-0.04	-0.02	0.02	0.1	0.75	0.75	0.25	-0.13	0	0.25	0.38	-0.02
a15	-0.1	0.04	-0.06	-0.02	-0.02	0.25	0.63	0.13	0.13	0.25	0.25	0.00	-0.09
d15	-0.08	0	0.08	0.14	0.12	0.75	0.50	0.25	0.00	0	0	0.25	-0.02
a16	-0.1	0	-0.1	-0.08	-0.1	0.50	0.75	0.38	0.50	0.25	0	0.13	-0.1
d16	-0.1	0	-0.06	-0.08	-0.02	0.75	1.00	0.50	0.50	0	0	0.00	-0.08
a17	-0.06	0	-0.08	0	0	0.75	0.38	0.00	-0.13	0	0.25	0.13	-0.06
d17	-0.02	0.04	0.02	0.1	0.22	0.75	0.75	0.00	0.00	0.5	0.5	0.00	0.04
b18	-0.06	0	-0.08	0	0	0.75	0.38	0.00	-0.13	0	0.25	0.13	-0.06
d18	0.18	-0.08	0.14	0.2	0.2	4.25	1.75	2.75	0.25	0.5	0.5	2.50	0.35
b19	-0.1	0	-0.08	-0.08	0	0.75	0.75	0.50	0.50	0	0	0.00	-0.09
d19	0.22	0.02	0	0	0.2	-1.25	-0.75	-1.25	-0.50	0.5	0.25	0.76	0.02
b20	-0.1	0	0.18	0.22	0.16	1.00	1.25	0.38	0.50	0.25	0	0.13	-0.09
d20	-0.1	0.02	-0.08	-0.02	-0.04	-1.50	-1.50	-1.75	-1.75	0	0	0.00	-0.08
b21	-0.08	-0.02	-0.08	-0.06	0	1.50	3.25	0.50	1.25	0	0.5	0.75	-0.08
d21	-0.06	0	0.14	0.14	0.14	1.63	4.25	0.88	2.75	0.75	0.5	1.88	-0.07
b22	-0.24	0.14	0.12	-0.18	0.22	0.88	1.25	0.50	0.75	0.5	0	0.25	-0.08
d22	-0.02	0.04	0.18	0.18	0.16	1.13	0.50	0.50	0.25	0	0	0.25	-0.02
a23	-0.08	0	-0.06	0.06	0.04	0.75	0.63	0.25	0.00	0	0	0.25	-0.06

d23	0.12	0.18	0	0.16	0.12	-0.25	-0.50	-0.75	-0.50	0	0	0.25	-0.01
b24	0.18	0	0.1	0.1	0.1	3.50	2.50	3.50	2.50	2	0	1.00	0.3
d24	-0.02	0.06	0.24	0.16	0.16	0.88	0.63	0.25	0.25	0	0	0.00	-0.05
b25	-0.08	0.06	-0.08	-0.08	-0.06	1.00	1.38	0.13	0.00	0.25	0.5	0.13	-0.06
d25	-0.06	0.04	0	0.1	0.12	1.00	1.00	0.25	0.50	0	0	0.25	-0.03
a26	0.1	0.08	-0.04	0.06	0.08	-0.88	-0.63	-0.50	-0.50	0	0	0.00	-0.08
d26	-0.08	-0.02	-0.08	0	0.32	7.25	9.00	6.75	8.00	0.5	2	1.25	0.21
b27	-0.1	0	-0.1	-0.04	-0.04	0.63	1.00	0.63	0.50	0.25	0.5	0.13	-0.1
d27	-0.1	0.08	0.1	0.14	0.14	2.00	0.88	0.50	0.38	0	0.25	0.13	-0.06
a28	-0.1	0	0.06	0.02	0.08	1.13	1.00	0.63	0.75	0.25	0	0.13	-0.1
d28	-0.04	0.06	-0.04	0.1	0.1	0.75	0.50	0.13	0.25	0.25	0	0.13	-0.02
d29	-0.1	0	0	0	0	0.75	0.75	0.50	0.38	0	0.25	0.13	-0.1
d30	0.04	0.18	0.04	0.14	0.12	-1.00	-1.00	-1.50	-1.75	0	0	0.25	-0.01
d31	-0.02	0	-0.1	-0.1	-0.1	0.75	0.50	0.25	0.25	0	0	0.00	-0.06
d32	-0.06	0	-0.02	0.1	-0.04	0.75	0.88	0.38	0.38	0.25	0.25	0.00	-0.08
d33	-0.08	-0.02	-0.04	0.08	0.08	1.50	1.75	0.88	1.13	0.25	0.25	0.25	-0.08
d34	-0.06	0	-0.08	-0.06	0	0.75	0.87	0.75	0.75	0	0	0.00	-0.06
d35	-0.1	0	-0.02	-0.04	0.06	0.63	0.75	0.50	0.50	0	0	0.00	-0.1
d36	-0.08	0	0	0.04	0.12	0.50	0.75	0.13	0.38	0.25	0.25	0.25	-0.09
d37	0.04	0	0.18	0.16	0.24	0.75	1.25	0.38	0.50	0.25	0	0.13	0
d38	-0.02	-0.06	0.14	0.2	0.2	1.00	1.00	-0.25	-0.13	0.5	0.25	0.13	-0.03
d39	-0.02	0.1	0.12	0.22	0.2	0.38	0.75	0.13	0.25	0.75	0.5	0.13	0.04
b29	-0.02	0.14	0.16	0.24	0.16	0.88	1.00	0.25	0.13	1	0.75	0.13	-0.03
a30	-0.1	0	-0.1	-0.08	-0.08	0.88	1.13	0.50	0.37	0	0	0.13	-0.1
b31	-0.02	0	0	0.16	0.1	0.25	0.38	0.38	0.38	0.75	0.25	0.00	-0.08
a32	0.18	0.04	-0.06	0	-0.02	-0.75	-0.63	-0.87	-0.75	0.5	0.5	0.12	-0.07
b33	-0.1	0.02	-0.08	-0.06	-0.1	0.50	0.75	0.25	0.50	0.5	0	0.25	-0.08
b34	-0.1	0.02	0.04	0.02	0.04	1.00	-0.25	0.50	-0.63	0	0.25	1.13	-0.1
b35	-0.01	-0.09	-0.08	0.02	-0.08	1.00	1.00	0.25	0.25	0	0	0.00	-0.08
a36	-0.1	0.04	0.06	0.14	0.06	0.50	0.75	0.12	-0.13	0	0.25	0.25	-0.07
b37	-0.1	0.02	-0.1	0.4	0.14	0.25	0.75	0.38	0.38	0.25	0.25	0.00	-0.06
b38	-0.08	-0.02	-0.08	-0.08	0.04	1.00	1.00	0.38	0.25	0.25	0	0.13	-0.1
a39	-0.08	0.02	-0.1	0	0	1.25	1.13	0.75	0.75	0	0	0.00	-0.08
b40	-0.1	0.02	-0.08	-0.06	0.02	1.00	1.25	0.38	0.25	0.25	0	0.13	-0.08
b41	0	0.18	-0.02	0.08	0.16	1.38	0.50	0.38	0.13	0.25	0.25	0.25	0.05
b42	0.48	0.06	-0.08	-0.02	-0.06	-2.25	-1.75	-2.75	-2.13	0.5	0.25	0.63	-0.05
b43	-0.1	0	-0.1	-0.08	-0.04	0.38	0.75	0.50	0.75	0	0	0.25	-0.1

Table A4.4 Raw data for refractive tests in main study. The abbreviations, in addition to those already defined, are as follows: "B" = binocular; "D" = distance; "M" = monocular; "best M. D - B D" = best monocular distance V/A minus binocular distance V/A; "N" = near; "R" = right eye; "L" = left eye; "ret" = retinoscopy; "sub" = subjective; "cyl" = cylinder; "anisomet." = anisometropia; "corr" = corrected.

ref.	CTN Hz	DTD Hz	abs DTD Hz	DTD Vt	DTN HZ	abd DTN Vt	DTN stab	ATN Hz	abs ATN Vt	ATN mot stab	FDN sens stab	NPC (Δ)	NPC-rec (Δ)
b01	0	1.5	1.5	1	-1	0	1	2	0	1	0	47.7	0.0
d01	0	-3	3	0	-0.5	0	0	0	0	0	1	31.8	-4.0
b02	0	-8	8	0.5	1	0	1	0	0	0	1	38.1	2.4
d02	3	-1	1	0	0	0	0	0	0	0	0	35.7	-1.2
a03	0	0	0	0	0	0	2	-0.5	0.5	1	1	45.8	1.8
d03	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	0	nd	nd
b04	0	-2	2	0	0	0.5	0	0	0	0	0	47.7	0.0
d04	0	0	0	5	-2.5	4	2.5	nd	0	nd	0	21.1	-2.7
a05	0	0	0	0	0	0	0	0	0	1	0	42.1	2.6
d05	0	0.5	0.5	0	0	0	0	0	0	0	0	47.7	0.0
b06	0	-5	5	1	-4	0	1	-2	0	1	1	44.0	3.2
d06	-2	nd	nd	nd	-1	0	0	-0.5	0	1	0	47.7	1.9
a07	0	-1	1	0	0	0	0	0	0	0	0	47.7	0.0
d07	2	0	0	0	3	0	1	0	0	0	1	47.7	0.0
a08	0	-5.5	5.5	0	-0.5	0	0.5	-2	0.5	1	1	34.7	-1.1
d08	-1	-1	1	0	0	0	0	0	0	0	0	40.9	1.4
a09	0	-3	3	0.75	0	0	1	0.5	0	1	0	47.7	0.0
d09	1	-1	1	0	-3	2	0	-1	1	1	1	28.6	0.7
b10	0	-2	2	1	0	0	0	0	0	0	1	38.1	-5.9
d10	0	-3	3	0	-1	0	5	-3	0	1	1	35.7	2.1
b11	0	0	0	1	1	0	1	2	0	1	0	38.1	0.0
d11	-1	-2.5	2.5	0	-5	0	2	0	0	0	1	27.2	4.4
b12	2	-0.5	0.5	0.5	2	0	2	2	0.5	0	1	44.0	3.2
d12	0	-4	4	0	-3	0	1	0	0.5	1	0	47.7	0.0
a13	0	-7	7	1	-3	0	0	0	0	0	0	47.7	0.0
d13	3	-1	1	1	4	0	2	0	1	1	1	47.7	0.0
a14	0	0.5	0.5	0	4	0	0	0	0.75	1	0	45.8	6.4
d14	0	-2.5	2.5	0	0	0	0	0	0.5	0	1	45.8	11.2
a15	1	-1.5	1.5	0	0	0	0	0	0	0	1	28.6	4.8
d15	3	2	2	0	4	0	4	1	0	0	0	47.7	0.0
a16	4	0	0	0	0	0	0	3	0	0	0	47.7	0.8
d16	0	-6.5	6.5	0	0	0	0	0	0.5	1	0	30.9	-2.7
a17	0	-2	2	1	-1	0	0	0	0	0	1	47.7	5.3
d17	0	-2	2	0	0	0	0	0	0	0	1	47.7	0.0
b18	0	-3	3	1	-0.5	0	0.5	0	0	0	1	42.4	2.9
d18	4	0.5	0.5	1	6	0	2	0	0	0	0	15.0	1.1
b19	0	-1.5	1.5	0.5	1	0	0	0	0	1	1	47.7	0.0
d19	1	-1	1	1	2	0	2	1	0	0	0	47.7	3.7
b20	8	-2	2	0	6	0	2	1	0	1	0	9.8	0.6
d20	0	-0.5	0.5	0.5	0	0	0.5	0.5	0	1	1	47.7	0.0
b21	0	-1.5	1.5	0	0	0	0	1	0	1	1	27.2	1.8
d21	2	-2	2	0	-2	0	1	0	0	0	1	47.7	0.0
b22	0	-1	1	0	0	0	0	0	0	0	0	47.7	0.0
d22	0	-1	1	0	-1	0	1.5	-0.5	0	1	0	38.1	4.5
a23	0	-1.5	1.5	0	-0.5	0	0.5	-0.5	0	0	0	47.7	0.0
d23	0	-1	1	0	1	0	1	0	0	1	1	47.7	0.0

b24	1	nd	nd	nd	2	0	0	0	0	0	0	47.7	0.0
d24	4	0	0	0	1.5	0	0.5	1	0	1	1	16.3	-1.0
b25	1	-3	3	1	2	0	0	0.5	0	0	0	35.7	16.1
d25	0	-2.5	2.5	2	0	0.5	0	0	0	0	0	31.8	0.9
a26	0	-4	4	1	-2	0	2	-1	0	1	0	32.7	-1.0
d26	-3	-3	3	0	-3	0.5	2	-1	0	1	1	47.7	3.7
b27	0	-1.5	1.5	0	0	0	0	0	0	1	1	44.0	3.2
d27	0	0	0	1	0	0	0	0	0.5	1	0	25.4	3.4
a28	0	-1	1	0	0	0	1	0	0	0	1	47.7	0.0
d28	0	-3	3	0	0	0	0	0.5	0	1	0	47.7	0.0
d29	2	2	2	0	1	0	1	0.5	0	1	0	47.7	0.0
d30	-1	-2	2	0	-3	0	2	-0.5	0	0	0	47.7	0.0
d31	1	nd	nd	nd	2	0	1	1	0	0	0	47.7	0.0
d32	0	-5	5	0	0	0	0	0	0	0	0	47.7	14.1
d33	2	-2	2	0.5	1.5	0	1	1	0	1	1	32.7	4.8
d34	0	1	1	0.5	0	0	0	0	0	0	0	47.7	0.0
d35	0	0	0	0	1	0	1	0	0	0	0	47.7	1.9
d36	4	-1	1	0	0	0	0	0.5	0	1	1	25.4	6.4
d37	2	-1	1	0.5	1	0	0	0	0	0	0	47.7	0.0
d38	4	-1	1	0	3.5	0	2.5	0.5	0.5	1	1	42.4	2.9
d39	0	-3	3	0	-0.5	0	0	0	0	1	1	47.7	3.7
b29	0	-3	3	0	-2	0	1	0	0	0	1	44.0	3.2
a30	0	-1	1	0	0	0	0	0	0	0	0	47.7	0.0
b31	0	-3	3	0	0	0	0	0	0	0	0	47.7	0.0
a32	0	-1	1	0	-1	0	0	0	0	0	0	47.7	0.0
b33	0	0	0	1	-1	0	0	1	0	1	1	38.1	2.4
b34	2	-1	1	0	-1	0	0	1	0.5	0	1	44.0	0.0
b35	0	-2.5	2.5	0.5	-1	0	0	0	0	1	1	38.1	4.5
a36	0	-2	2	1	-1	0	0	0	0	0	1	47.7	3.7
b37	-2	-8.5	8.5	0	-9	0	0	0	0	0	0	47.7	0.0
b38	0	-4	4	1	0	0	0	-1	0	0	1	47.7	0.0
a39	2	-1	1	0	2	0	0	0.5	0.5	1	1	47.7	0.0
b40	0	-1.5	1.5	0	0	0	0	0.5	0	1	1	47.7	0.0
b41	0	0	0	0	3	0	1	0.5	0	1	1	47.7	0.0
b42	1	-2	2	0.5	-0.5	0	0.5	0	0	1	0	47.7	0.0
b43	1	-0.5	0.5	0	3	0	1	0	0	0	0	44.0	5.9

Table A4.5 Raw data for binocular vision and orthoptic tests in main study (continued in Table A4.6). The abbreviations, in addition to those already defined, are as follows: "CT" = cover test; "Hz" = horizontal; "DT" = dissociation test; "abs" = absolute; "Vt" = vertical; "AT" = associated test of heterophoria; "mot" = motor; "stab" = stability; "sens" = sensory; and "rec" = recovery.

ref.	base in blur	base in break	base in rec.	base out blur	base out break	base out recov.	stereo-psis 80 cm	AC/A ratio	B status R-L
b01	20	21	12.5	31.5	37	29.5	20	3.67	0.15
d01	nd	14.5	9	nd	6.5	2.25	30	2.5	-0.08
b02	nd	7.5	3.5	nd	10.5	6.5	100	3.33	0.20
d02	nd	19	15	nd	16	11.5	20	2.67	0.00
a03	11.3	15.3	13	3	5.7	1.5	20	2.33	0.00
d03	nd	nd	nd	nd	nd	nd	200	nd	0.52
b04	15	16.5	8	nd	18.5	6	20	1.67	-0.06
d04	1	5.5	3	nd	7.5	2	400	4.5	0.00
a05	nd	15.75	12	35.75	30.5	29	25	2.33	0.08
d05	nd	13.5	11.5	14.5	16.5	8	20	2.67	0.00
b06	nd	11	2	21	23	15.5	20	3.67	0.08
d06	nd	6.5	4.5	nd	23	19.5	30	4.67	0.07
a07	nd	27.5	20	nd	28	23.5	70	5.2	-0.15
d07	14	14	13	11.5	15.5	9	20	2	-0.60
a08	nd	11.5	3.5	21.5	23	11.5	30	4.83	0.15
d08	12.5	19	16.25	nd	16.5	9.25	20	4.67	0.00
a09	nd	10.5	10	nd	16.5	14.5	20	6	0.00
d09	5.75	9	6.5	7	10.5	6.25	20	3	0.00
b10	nd	9	5.25	nd	6.5	2.25	50	2	-0.60
d10	3.2	4.8	3.3	2.3	3.7	2	50	1.8	-0.10
b11	22	29	27	nd	24.5	14	25	3.33	-0.27
d11	nd	10.25	4	nd	20	9	30	4	0.08
b12	7.75	10.75	8.75	18	21	19.7	200	4.67	0.00
d12	nd	12	5	nd	26	14	20	8	-0.07
a13	40	40	40	nd	19	16.5	100	2.33	0.12
d13	10.25	12.5	10.25	9	17.5	6.5	40	3	0.22
a14	12.3	18	11.7	nd	7.5	1	40	2.67	-0.06
d14	nd	12.75	6.25	7.7	18.3	4.3	20	2.4	0.18
a15	5	10.25	7.75	10.8	17.2	12.2	20	4	-0.08
d15	10	12.5	9.5	nd	8.5	1	70	4	0.46
a16	nd	17.75	12.25	nd	16	8.7	20	2.33	0.00
d16	6	19.25	4.75	nd	9	6	20	2.33	0.00
a17	11	17	10.5	nd	22	8.3	25	3	0.00
d17	10.25	22.75	11	nd	23	20	70	3.5	-0.08
b18	nd	13	8.5	nd	12	3.75	20	2.25	0.00
d18	3.5	4.5	2.5	3	8.9	6	200	1.67	0.60
b19	nd	13.5	12	nd	29.7	32	30	4.67	-0.48
d19	nd	22.5	13	nd	8	4.5	20	0.67	-0.07
b20	13	21	17	nd	10.5	4.5	20	1.67	0.00
d20	6	9	6.5	20	27.5	24	20	5.5	0.00
b21	15	21.5	18	nd	9	2	40	1.33	-0.30
d21	19.5	26	25	13.5	26.5	24.5	40	2.67	-0.30
b22	14	16	15	nd	23.5	19.5	20	3.67	0.00
d22	4	6.5	5.5	nd	6.5	5	50	3.33	0.18
a23	nd	9.75	5.5	nd	14.5	10	70	3.17	0.00
d23	9	13.5	11	nd	10	5	200	4.67	0.00

b24	nd	25	22	nd	28	22	400	3	0.00
d24	5.3	9	6	3.5	6.5	2.5	40	1.5	-0.18
b25	nd	20.5	13.5	nd	10.5	2.5	20	2.33	-0.06
d25	nd	15.7	7.7	nd	22	14	70	3.67	0.00
a26	nd	8.5	3	15	16	12	20	3.67	0.00
d26	nd	5	-4	nd	16	7	50	3.5	-0.60
b27	15.5	16.5	14.5	22	26	17.75	20	2	0.00
d27	9	9.5	6.75	nd	12.5	9	20	3	0.00
a28	10	13.5	10	0	15	8.5	20	3.33	-0.15
d28	nd	19.5	15.5	nd	12.5	11	20	3	0.08
d29	nd	22.5	18	17	18.5	14	20	2	0.10
d30	9.3	12.7	3	nd	22.5	14	70	4.5	-0.08
d31	16.5	17	15.5	16	18.5	16.5	20	2.33	0.00
d32	14.5	17.5	9	11	16.5	6.5	20	2.67	0.00
d33	nd	15.5	6	nd	10.7	4.8	25	2.5	0.00
d34	11.5	13.5	10.5	nd	28.5	18	20	4.33	-0.11
d35	11	15	9.5	nd	10	4	30	3.33	-0.08
d36	nd	11.7	9.7	nd	16.2	10.3	20	3.67	0.00
d37	9.5	10	9	15.8	24.7	20.3	50	2	-0.46
d38	12.5	17	12.5	12.3	14.3	9.3	25	2.17	0.08
d39	14	14.5	13.5	nd	10.5	-1	20	2.83	-0.07
b29	13.5	17.25	3.75	nd	22.3	11.5	20	4	0.00
a30	13.5	16.5	15.5	nd	19	12	20	1.67	0.00
b31	nd	13.5	6.75	18	30	30	30	2.67	0.00
a32	nd	14.75	13.5	nd	16	14	25	3.2	0.00
b33	nd	14.5	10.5	nd	12	5.5	20	5	0.00
b34	11	14.5	6	11.5	12.5	10.5	20	4.67	0.20
b35	9	14.5	12.25	nd	15.5	11.5	20	3.33	0.15
a36	nd	10.75	5	6	10	3.75	30	1.55	0.08
b37	nd	8.5	3.5	nd	34.5	14.5	20	3	-0.15
b38	nd	15.5	14	17.3	25.2	11.3	30	3	-0.08
a39	nd	13	9.5	nd	13	4	20	2.33	-0.40
b40	nd	14.25	12.25	24	21.7	15.3	20	3	0.00
b41	nd	20.5	16.25	12	14	3	30	0.66	-0.15
b42	11	15.5	7	nd	28.5	13.75	70	4.75	0.15
b43	nd	20	14.25	nd	23	15	25	1.67	0.00

Table A4.6 Raw data for binocular vision and orthoptic tests in main study (continued from Table A4.5). Columns 2-7 refer to the prism vergences.

ref.	R acc lag	L acc lag	R acc amp	L acc amp	B acc amp	DN 30"	DN 60"	DN 90"	DN/N 30"	DN/N 60"	DN/N 90"
b01	0.75	1	13	14	16	13	23	33	0.867	0.767	0.805
d01	1.5	1.5	17	17	16	9	15	22	0.818	0.750	0.733
b02	0.75	0.75	16	20	21	9	18	24	0.600	0.621	0.585
d02	1.25	1	12	14	16	10	17	26	0.833	0.739	0.743
a03	1	1	17	19	19	8	16	23	0.800	0.727	0.697
d03	0.5	0.5	13	17	18	8	13	18	0.889	0.813	0.783
b04	0.75	0.75	20	20	21	14	22	33	0.933	0.759	0.805
d04	1	1	7	8	7.5	2	3	5	0.667	0.600	0.833
a05	1.25	1.25	20	20	20	17	31	45	0.895	0.939	0.900
d05	1.25	1.25	9.5	9	16	9	16	23	0.750	0.640	0.622
b06	1	1.25	16	16	17	12	23	34	0.857	0.793	0.810
d06	1	1.75	21	20	21	7	12	17	1.167	1.091	1.063
a07	1	1.25	21	21	21	12	22	32	0.800	0.733	0.696
d07	1	1.25	14	14	15	11	21	28	0.917	0.875	0.824
a08	1.75	1	16	18	20	18	31	47	1.059	0.939	0.940
d08	0.87	0.87	13	16	18	9	16	20	0.900	0.842	0.714
a09	0.75	1.25	21	21	21	12	23	32	0.750	0.767	0.711
d09	1.5	1.5	6.5	6.75	7	nd	nd	nd	nd	nd	nd
b10	0.75	0.75	12	15	19	11	19	26	0.688	0.633	0.565
d10	1.25	1.25	7.5	7.5	7.5	4	7	12	0.571	0.583	0.706
b11	1.25	1.5	13	14	20	11	21	30	0.688	0.677	0.698
d11	0.87	0.87	7	7	8.5	11	18	24	1.000	0.857	0.800
b12	1	0.75	14	13	14	12	22	32	0.857	0.786	0.800
d12	1.37	1.37	19	21	18	7	14	20	0.538	0.667	0.690
a13	1	1	18	20	21	15	22	31	1.364	0.917	0.816
d13	0.87	0.87	15	13	16	6	8	12	1.000	0.667	0.667
a14	1	1	20	21	20	7	13	19	0.778	0.722	0.633
d14	0.5	0.5	18	17	20	2	4	7	0.333	0.364	0.583
a15	1.5	1.5	8.75	9.5	9	14	24	33	0.933	0.828	0.767
d15	0.62	0.62	13	14	15	12	20	28	1.200	0.952	0.875
a16	1	1	17	19	20	14	23	34	0.933	0.767	0.756
d16	1.5	1.25	14	13	18	8	12	17	0.727	0.667	0.708
a17	1.25	1.25	17	18	19	13	23	30	0.929	0.885	0.769
d17	0.5	0.5	12	12	13	8	15	20	0.800	0.882	0.800
b18	1.25	1.25	18	18	17	13	21	28	0.813	0.778	0.778
d18	1.25	1.25	10.5	17	12	nd	nd	nd	nd	nd	nd
b19	1	1.25	18	19	21	11	18	26	0.786	0.692	0.703
d19	-0.25	-0.25	15	11	20	7	12	16	0.875	0.857	0.727
b20	1.5	1.25	9	7.5	10	14	26	41	0.778	0.765	0.804
d20	0.75	1	18	18	18	9	15	23	0.900	0.750	0.793
b21	1	2.25	10	11	20	16	27	41	0.842	0.730	0.774
d21	0.75	1	16	16	18	9	12	16	nd	nd	nd
b22	nd	nd	18	20	20	12	20	29	0.857	0.769	0.725
d22	1	1	12	12	20	13	21	30	nd	nd	nd
a23	1.25	1.25	21	21	21	16	30	43	0.800	0.732	0.768
d23	0.75	0.75	18	20	21	11	20	29	0.786	0.741	0.707

b24	0.75	0.75	20	20	20	10	18	27	0.769	0.692	0.750
d24	1.25	1.5	4	4	4	12	20	30	0.923	0.800	0.882
b25	1.25	1.5	19	18	20	12	22	31	0.857	0.815	0.795
d25	1.25	1.25	15	17	15	9	17	24	0.818	0.895	0.828
a26	0.5	0.5	17	18	20	11	22	31	0.733	0.786	0.775
d26	1	1.5	12	11	13.5	11	19	26	1.222	1.056	1.000
b27	0.75	0.75	15	15	19	9	16	21	0.900	0.762	0.656
d27	1	1	6.5	7	9	8	15	22	1.000	0.938	0.957
a28	1.25	1.25	20	20	20	10	17	23	0.667	0.607	0.575
d28	0.5	0.5	20	20	20	11	19	27	0.917	0.826	0.844
d29	0.62	0.62	18	18	21	6	14	21	0.667	0.824	0.875
d30	0.75	1	20	20	21	7	13	18	1.000	1.083	1.059
d31	0.75	0.5	10.5	10.5	16	14	25	34	nd	nd	nd
d32	1	1	14	14	17	8	13	18	0.889	0.813	0.783
d33	1.75	1.75	10	10.5	13	9	17	21	0.750	0.773	0.700
d34	1	1	18	17	18	13	21	30	1.000	0.840	0.857
d35	1	1	21	21	21	5	8	10	1.000	0.727	0.625
d36	1.5	1.75	8.5	9.5	11	11	22	33	1.000	0.957	0.971
d37	0.75	1	20	14	20	10	17	23	0.909	1.000	0.958
d38	1.25	1.25	15	15	19	8	15	21	0.889	0.882	0.840
d39	0.5	0.5	13	13	16	6	10	14	1.000	0.909	0.933
b29	0.5	0.5	18	17	17	14	27	38	0.778	0.750	0.717
a30	1.12	1.12	16	17	16	12	24	36	0.706	0.774	0.750
b31	0.5	0.25	16	18	20	10	21	31	0.625	0.700	0.705
a32	0.75	0.75	20	18	21	17	29	45	0.708	0.630	0.662
b33	0.5	0.5	13	14	16	15	27	40	1.154	1.000	0.976
b34	0.75	0.25	16	15	14	12	23	33	0.857	0.821	0.786
b35	1.25	1.25	19	17	19	16	24	34	0.941	0.750	0.708
a36	0.75	0.75	15	14	19	13	22	29	0.929	0.759	0.707
b37	0.75	0.75	21	21	21	11	20	24	1.000	0.952	0.800
b38	0.75	0.75	18	18	20	15	26	38	0.938	0.867	0.844
a39	1	1	19	20	19	8	15	21	0.727	0.789	0.750
b40	1	1	20	18	20	8	16	21	0.889	0.889	0.808
b41	1	0.62	13	15	17	6	13	15	0.750	1.000	0.789
b42	0.25	0.25	17	16	21	16	27	40	1.231	1.000	1.026
b43	1	1.25	17	16	20	11	19	25	0.917	0.826	0.781

Table A4.7 Raw data for accommodative tests in main study. The abbreviations, in addition to those already defined, are as follows: "acc" = accommodative; "amp" = amplitude; and the abbreviations for the dynamic assessment of accommodation and convergence are explained in Section 8.3.4.3.

reference	dom. eye	n/10 dom.	n/10 Δ	resp.
b01	R	9	7	nd
d01	B	5	10	3
b02	L	6	10	3
d02	L	9	10	5
a03	R	8	10	3
d03	nd	nd	nd	nd
b04	L	9	10	3
d04	L	nd	nd	nd
a05	R	9	10	5
d05	R	6	10	3
b06	R	6	3	2
d06	L	10	9	4
a07	R	6	10	3
d07	R	7	9	2
a08	L	10	10	5
d08	L	6	10	3
a09	L	9	10	4
d09	L	6	5	3
b10	R	6	10	3
d10	R	6	0	3
b11	R	6	0	nd
d11	R	7	10	4
b12	L	7	0	4
d12	L	7	10	3
a13	L	7	10	3
d13	R	6	10	3
a14	L	9	10	3
d14	L	7	10	2
a15	R	6	10	4
d15	L	7	0	nd
a16	L	7	8	3
d16	L	6	10	3
a17	B	5	10	4
d17	R	9	10	5
b18	L	7	10	3
d18	L	9	4	4
b19	R	6	10	2
d19	R	7	5	2
b20	L	7	nd	nd
d20	L	7	5	5
b21	R	10	10	5
d21	R	7	nd	nd
b22	L	6	10	nd
d22	L	7	nd	nd
a23	R	8	10	5
d23	L	6	10	2
b24	L	10	4	4
d24	R	6	8	3
b25	R	8	10	3
d25	L	7	10	3
a26	L	7	10	4
d26	R	8	9	3
b27	B	5	10	3
d27	L	7	8	4
a28	R	6	10	4
d28	B	5	10	3
d29	L	9	0	
d30	B	5	10	3
d31	R	7	nd	nd
d32	nd	nd	nd	nd
d33	R	8	10	3
d34	L	6	10	3
d35	L	6	10	2
d36	B	5	nd	nd
d37	L	7	8	2
d38	B	5	10	2
d39	L	6	10	3
b29	R	7	10	4
a30	R	7	10	3
b31	L	6	10	nd
a32	L	8	10	3
b33	B	5	nd	nd
b34	L	9	0	nd
b35	L	6	10	4
a36	R	8	10	4
b37	L	9	9	3
b38	L	8	9	5
a39	L	7	10	3
b40	L	6	10	5
b41	L	9	10	3
b42	R	6	0	3
b43	B	5	1	4

Table A4.8 Raw data for Dunlop Test in main study. The abbreviations, in addition to those already defined, are as follows: "dom." = dominant eye; "n/10 dom." = the number of times out of 10 trials that the eye that was most often the dominant eye was the dominant eye; "n/10 Δ" = number of times out of 10 trials that prism was required to induce a fixation disparity; and "resp." = subjective grading of subject's response.

ref.	I co C	I be C	I bl C	I fl C	I sh C	I di C	I ot C	I co E	I be E	I bl E	I fl E	I sh E	I di E	I ot E	R E-C
b01	1	0	0	0	0	0	0	1	0	1	1	1	0	0	3
d01	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
b02	0	0	1	0	1	0	0	0	0	1	1	1	1	1	3.3
d02	0	0	0	0	0	0	0	0	0	0	0	1	1	1	3.1
a03	0	0	0	0	1	1	0	0	0	1	1	1	1	0	2.1
d03	1	1	0	0	0	1	0	0	0	1	1	1	1	1	2.2
b04	0	0	0	0	0	1	0	0	0	0	1	1	1	0	2
d04	0	0	0	0	0	0	0	1	1	1	0	1	1	0	5.2
a05	0	0	0	0	0	0	0	0	0	0	1	1	0	0	2
d05	0	0	0	0	0	0	0	0	0	1	1	1	0	0	3.2
b06	0	0	0	0	0	0	0	1	0	1	0	0	0	1	3.1
d06	0	0	0	0	0	0	0	1	1	1	1	1	0	0	5.1
a07	0	0	0	0	0	0	0	0	0	0	1	1	0	1	3.1
d07	0	0	0	0	0	0	0	0	0	0	1	1	0	1	3.1
a08	0	0	0	0	0	0	0	1	1	1	1	1	1	0	6.2
d08	0	0	0	0	1	0	0	0	0	0	1	1	0	0	1.1
a09	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
d09	1	0	1	0	0	0	0	1	0	1	0	1	1	0	2.1
b10	0	0	0	0	0	0	0	0	1	0	0	0	1	0	2
d10	0	0	0	1	1	0	0	0	0	1	0	0	1	0	0.1
b11	0	0	0	0	0	0	1	1	0	0	0	0	0	1	1
d11	0	0	1	0	0	0	0	0	0	0	1	1	1	1	3.1
b12	0	1	1	0	0	0	0	0	1	0	0	1	1	0	1.2
d12	0	0	0	0	0	0	0	1	0	0	1	0	1	0	3.1
a13	0	0	0	0	1	0	1	1	1	1	1	1	1	1	5.2
d13	0	0	0	0	1	1	0	1	1	0	1	1	0	1	3.3
a14	0	0	0	0	0	0	0	0	1	1	0	1	1	1	5.1
d14	0	1	1	1	1	1	0	0	1	0	1	1	1	0	-0.9
a15	0	0	0	0	0	0	0	1	1	1	0	0	0	0	3.2
d15	0	1	1	0	1	0	0	1	1	0	1	1	1	0	2.1
a16	0	0	0	0	0	0	0	0	0	1	1	1	1	0	4.1
d16	0	0	1	0	0	0	0	1	1	1	0	1	0	0	3.1
a17	0	0	0	0	0	0	0	0	1	0	1	0	0	0	2
d17	0	0	0	0	0	0	0	1	1	1	1	1	0	1	6.1
b18	0	0	0	0	1	0	0	0	0	0	1	1	1	1	3.4
d18	0	0	1	0	0	0	0	1	1	1	1	1	1	0	5.1
b19	0	0	0	0	0	0	0	0	0	1	0	0	1	0	2
d19	0	0	1	0	0	0	0	0	0	0	0	0	0	0	-1
b20	0	0	0	0	0	0	0	1	0	1	0	0	0	0	2
d20	0	1	0	0	1	0	0	0	1	1	1	1	1	1	4.4
b21	0	0	0	0	0	0	0	1	0	1	0	1	0	0	3
d21	0	0	1	1	0	0	0	0	0	1	1	0	0	1	1.5
b22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
d22	0	0	1	0	1	0	1	0	0	0	1	1	0	1	-0.2
a23	0	0	0	0	0	0	0	0	0	1	1	0	0	0	2
d23	0	1	0	0	0	0	0	0	1	1	1	1	1	1	5.5
b24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

d24	1	0	0	0	0	1	0	0	1	0	0	1	1	0	1.1
b25	0	0	0	1	1	0	0	0	0	0	0	1	0	0	-1
d25	0	0	0	0	0	0	0	1	0	0	1	0	0	0	2
a26	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1
d26	0	0	0	0	0	0	0	1	0	0	1	1	0	1	4
b27	0	0	0	0	0	0	0	0	0	1	0	1	0	1	3
d27	0	0	0	0	0	0	0	1	1	1	1	1	0	0	5.3
a28	0	0	0	1	0	0	0	0	0	1	1	1	1	1	4.1
d28	0	0	1	0	0	0	0	0	1	1	1	1	1	1	5.1
d29	0	0	0	0	1	0	0	0	1	1	1	1	0	1	4.6
d30	0	0	0	1	1	0	0	0	1	0	1	1	1	1	3.3
d31	0	0	0	0	0	0	0	0	1	1	1	1	0	0	4.1
d32	0	0	0	0	0	0	0	0	0	1	1	1	0	1	4.2
d33	0	0	0	0	0	0	0	0	1	1	0	0	0	0	2
d34	0	0	0	0	0	0	0	1	0	0	1	1	0	1	4.1
d35	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
d36	0	1	0	1	1	0	0	1	1	1	1	1	0	0	2.2
d37	0	1	0	0	0	0	0	1	1	0	0	1	0	0	2.2
d38	0	0	0	0	0	0	0	0	1	0	0	0	1	0	2.1
d39	0	0	0	0	0	0	0	1	1	0	0	1	0	0	3.1
b29	0	0	0	1	0	0	0	1	0	1	1	1	0	0	3
a30	0	0	0	0	0	0	0	0	0	1	1	1	0	0	3
b31	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1
a32	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
b33	0	0	0	0	0	0	0	0	1	1	0	0	1	0	3
b34	0	0	0	0	0	0	0	1	1	0	1	1	0	0	4.1
b35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
a36	0	0	0	0	0	0	1	0	1	0	1	1	0	1	3.2
b37	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
b38	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1
a39	0	0	0	0	1	0	0	0	1	1	0	1	1	1	4.3
b40	0	0	1	1	0	0	0	0	1	1	0	1	0	0	0.9
b41	0	0	1	0	0	0	0	0	0	1	1	0	0	1	2.2
b42	0	0	0	0	0	0	0	1	0	1	1	1	0	0	4
b43	0	0	0	0	0	0	0	0	0	1	1	1	1	1	5.1

Table A4.9 Raw data for pattern glare test in main study. The abbreviations, in addition to those already defined, are as follows: "I" = integer; "C" = control; "co" = colour; "be" = bending; "bl" = blurring; "fl" = flickering; "sh" = shimmering; "di" = disappearing; "ot" = other; "E" = experimental; "R" = real; and "E - C" = the sum of the experimental minus the sum of the control illusions. The terminology is further explained in Section 8.3.6.

ref.	1 c/°	2 c/°	4 c/°	8 c/°	12 c/°	flicker threshold
b01	70.0	170.0	260.0	170.0	65.0	0.00216
d01	30.0	57.7	145.0	125.0	65.0	0.00315
b02	86.7	158.3	210.0	142.7	65.0	0.00126
d02	35.0	71.3	165.0	100.3	40.0	0.00258
a03	35.0	85.0	125.0	100.3	48.3	0.00264
d03	58.3	128.0	145.0	88.0	40.0	0.00250
b04	35.0	85.0	125.0	88.0	40.0	0.00153
d04	10.3	21.0	31.7	39.7	11.7	0.00291
a05	86.7	141.7	165.0	112.7	48.3	0.00247
d05	35.0	113.3	165.0	100.3	40.0	nd
b06	120.0	170.0	185.0	125.0	90.0	0.00216
d06	35.0	57.7	106.7	100.3	56.7	0.00285
a07	103.3	170.0	190.0	142.7	65.0	0.00160
d07	46.7	71.3	106.7	112.7	40.0	0.00206
a08	75.0	158.3	210.0	112.7	48.3	0.00275
d08	86.7	71.3	185.0	100.3	65.0	0.00212
a09	46.7	128.0	165.0	140.0	81.7	0.00237
d09	25.0	30.7	45.0	58.3	27.0	0.00269
b10	35.0	113.3	165.0	112.7	15.0	0.00240
d10	58.3	128.0	138.3	125.0	52.0	0.00300
b11	120.0	170.0	185.0	125.0	65.0	0.00144
d11	58.3	57.7	125.0	100.3	48.3	0.00243
b12	58.3	170.0	133.3	127.7	35.3	0.00172
d12	75.0	71.3	190.0	140.0	65.0	0.00261
a13	86.7	186.7	165.0	125.0	65.0	0.00230
d13	46.7	99.7	170.0	155.0	73.3	0.00180
a14	136.7	141.7	190.0	125.0	65.0	0.00213
d14	58.3	71.3	165.0	88.0	65.0	0.00248
a15	58.0	71.0	165.0	118.3	65.0	0.00268
d15	35.0	85.0	185.0	125.0	65.0	nd
a16	86.7	170.0	185.0	155.0	81.7	0.00126
d16	70.0	113.3	125.0	112.7	48.3	0.00264
a17	46.7	71.3	165.0	140.0	40.0	0.00141
d17	86.7	175.0	235.0	140.0	81.7	0.00170
b18	41.0	158.3	165.0	127.7	48.3	0.00129
d18	35.0	85.0	165.0	100.3	56.7	0.00295
b19	106.0	175.0	165.0	88.0	65.0	0.00216
d19	35.0	71.3	125.0	88.0	35.3	0.00287
b20	35.0	170.0	185.0	125.0	65.0	0.00161
d20	103.3	186.7	165.0	112.7	81.7	0.00186
b21	58.3	186.7	210.0	127.7	81.7	0.00187
d21	77.5	220.0	185.0	106.5	90.0	nd
b22	35.0	85.0	125.0	125.0	40.0	0.00234
d22	70.0	170.0	185.0	125.0	65.0	nd
a23	86.7	113.3	190.0	140.0	65.0	0.00229
d23	86.7	113.3	145.0	125.0	65.0	0.00247
b24	86.7	141.7	170.0	112.7	65.0	0.00230

d24	46.7	71.3	125.0	88.0	40.0	0.00294
b25	46.7	113.3	210.0	140.0	73.3	0.00100
d25	46.7	71.3	125.0	88.0	48.3	nd
a26	35.0	71.3	125.0	100.3	48.3	0.00330
d26	120.0	186.7	190.0	125.0	73.3	0.00273
b27	103.3	141.7	165.0	125.0	65.0	0.00247
d27	35.0	44.0	53.3	88.0	40.0	0.00242
a28	63.3	141.7	165.0	127.7	65.0	0.00245
d28	35.0	57.7	88.3	100.3	40.0	0.00187
d29	170.0	170.0	185.0	125.0	90.0	0.00206
d30	35.0	44.0	98.3	88.0	40.0	nd
d31	120.0	85.0	125.0	88.0	40.0	nd
d32	35.0	85.0	125.0	88.0	40.0	0.00248
d33	46.7	85.0	125.0	88.0	40.0	nd
d34	70.0	130.0	235.0	127.7	90.0	nd
d35	75.0	144.7	125.0	112.7	90.0	nd
d36	58.3	113.3	235.0	112.7	90.0	0.00335
d37	46.7	71.3	146.7	127.7	56.7	0.00261
d38	58.3	130.0	210.0	100.3	65.0	0.00263
d39	75.0	71.3	145.0	100.3	81.7	0.00236
b29	70.0	141.7	210.0	140.0	48.3	0.00244
a30	120.0	141.7	235.0	140.0	90.0	nd
b31	120.0	170.0	185.0	170.0	65.0	nd
a32	58.3	170.0	190.0	142.7	56.7	0.00249
b33	170.0	220.0	185.0	125.0	90.0	0.00193
b34	120.0	220.0	185.0	125.0	65.0	0.00248
b35	103.3	170.0	235.0	140.0	90.0	0.00379
a36	75.0	141.7	215.0	155.0	73.3	0.00196
b37	120.0	170.0	235.0	140.0	73.3	0.00080
b38	120.0	85.0	185.0	170.0	65.0	0.00209
a39	46.7	158.3	235.0	127.7	40.0	0.00238
b40	103.3	113.3	165.0	125.0	56.7	0.00209
b41	103.3	141.7	165.0	125.0	65.0	0.00187
b42	103.3	175.0	210.0	125.0	90.0	0.00227
b43	136.7	186.7	125.0	125.0	65.0	0.00156

Table A4.10 Raw data for tests of parallel processing in main study. The table shows the mean spatial contrast sensitivity at 1 to 12 c/° and the contrast at the flicker threshold.

ref.	B3	B4	B5	BR	M3	M4	M5	MR	BE	RE	ALL
b01	205.6	181.3	200.0	182.5	258.8	187.5	198.8	163.8	192.3	202.2	197.3
d01	303.5	345.4	308.0	360.8	332.8	245.8	310.5	353.4	329.4	310.6	320.0
b02	252.5	202.5	171.3	185.5	238.8	191.5	201.3	223.1	202.9	213.7	208.3
d02	219.6	174.0	182.1	194.6	208.5	147.5	162.4	147.5	192.6	166.5	179.5
a03	207.5	166.0	181.5	190.5	235.3	186.3	181.6	174.3	186.4	194.3	190.4
d03	342.5	309.8	302.6	268.0	375.0	300.3	311.5	300.5	305.7	321.8	313.8
b04	205.8	157.3	159.8	181.0	200.8	208.0	175.8	154.3	175.9	184.7	180.3
d04	152.9	186.5	230.8	173.5	239.8	161.3	179.3	179.8	185.9	190.0	188.0
a05	196.8	142.0	130.0	151.0	169.0	162.5	154.3	124.3	154.9	152.5	153.7
d05	230.8	172.0	166.5	223.3	216.0	226.0	184.8	192.5	198.1	204.8	201.5
b06	202.5	161.3	166.3	170.0	232.5	173.8	160.0	182.5	175.0	187.2	181.1
d06	272.8	199.0	188.5	222.8	259.1	204.0	230.0	200.6	220.8	223.4	222.1
a07	197.3	134.8	126.5	150.0	164.3	146.0	152.0	126.0	152.1	147.1	149.6
d07	188.5	148.4	169.5	187.0	188.1	158.3	171.1	148.4	173.3	166.5	169.9
a08	210.0	187.8	194.3	185.5	199.5	169.8	174.0	158.8	194.4	175.5	184.9
d08	213.8	180.0	195.0	171.9	209.0	173.3	175.0	160.0	190.2	179.3	184.7
a09	265.3	187.8	186.0	245.3	300.8	249.3	227.8	197.0	221.1	243.7	232.4
d09	234.0	182.3	193.8	190.3	212.9	216.9	194.6	175.0	200.1	199.8	200.0
b10	293.0	213.8	245.8	226.3	263.3	217.8	225.8	180.3	244.7	221.8	233.2
d10	379.0	226.8	202.8	234.4	265.5	289.5	242.0	268.8	260.7	266.4	263.6
b11	171.3	166.3	146.3	171.3	186.3	147.5	150.0	136.3	163.8	155.0	159.4
d11	292.0	204.3	178.3	369.5	332.0	231.8	223.8	268.8	261.0	264.1	262.5
b12	267.8	183.3	192.3	179.3	227.0	213.5	198.8	146.0	205.6	196.3	201.0
d12	322.3	287.0	267.5	280.6	338.6	248.5	231.5	256.5	289.3	268.8	279.1
a13	201.0	160.5	142.5	169.3	197.3	152.6	157.0	158.3	168.3	166.3	167.3
d13	315.5	246.8	202.1	301.5	331.3	294.8	279.8	241.3	266.5	286.8	276.6
a14	330.5	288.5	288.5	248.5	344.1	257.8	239.6	265.3	289.0	276.7	282.8
d14	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
a15	179.8	138.0	134.4	145.5	160.5	161.5	151.8	125.8	149.4	149.9	149.6
d15	290.0	205.0	223.8	218.8	265.0	256.3	230.0	206.3	234.4	239.4	236.9
a16	277.8	176.0	149.0	178.1	199.8	197.3	176.3	137.0	195.2	177.6	186.4
d16	213.3	241.8	220.4	241.5	276.8	235.8	269.0	181.4	229.2	240.7	235.0
a17	293.6	242.0	248.9	200.3	281.8	294.9	263.0	231.8	246.2	267.8	257.0
d17	294.8	248.3	221.3	253.4	265.0	261.3	271.4	215.9	254.4	253.4	253.9
b18	282.5	230.0	249.0	280.0	294.0	278.3	294.9	236.8	260.4	276.0	268.2
d18	477.3	282.3	206.0	291.6	370.5	332.0	321.5	280.0	314.3	326.0	320.1
b19	223.3	179.0	242.5	168.8	236.3	180.0	165.3	172.6	203.4	188.5	196.0
d19	377.8	244.3	177.0	289.5	249.3	315.3	251.3	265.3	272.1	270.3	271.2
b20	204.0	156.5	146.3	154.8	173.5	163.3	142.5	156.3	165.4	158.9	162.1
d20	262.3	187.5	175.3	236.0	230.8	241.8	229.0	186.3	215.3	221.9	218.6
b21	182.0	142.8	124.5	172.8	191.0	169.3	163.8	123.3	155.5	161.8	158.7
d21	285.0	185.0	167.5	210.0	235.0	218.8	185.0	170.0	211.9	202.2	207.0
b22	281.3	203.8	192.5	226.3	266.3	213.8	252.5	193.8	225.9	231.6	228.8
d22	191.3	125.0	133.8	185.0	196.3	210.0	160.0	156.3	158.8	180.6	169.7
a23	250.3	210.5	218.0	224.8	218.0	209.8	217.3	237.8	225.9	220.7	223.3
d23	173.8	147.3	138.0	135.8	182.0	149.3	152.3	173.3	148.7	164.2	156.4
b24	301.8	198.5	177.3	241.5	275.8	217.3	244.0	208.0	229.8	236.3	233.0
d24	226.3	193.3	205.3	187.0	231.3	164.0	161.3	194.3	202.9	187.7	195.3

b25	227.3	188.8	186.0	217.1	256.5	203.8	240.6	193.8	204.8	223.7	214.2
d25	180.3	155.3	160.0	184.5	182.5	136.9	156.3	155.3	170.0	157.7	163.9
a26	308.0	217.3	237.0	243.8	279.3	269.3	252.3	252.3	251.5	263.3	257.4
d26	233.0	182.5	150.8	223.8	207.5	192.5	206.3	225.0	197.5	207.8	202.7
b27	265.0	172.9	162.8	210.8	214.5	329.3	195.5	195.5	202.8	233.7	218.3
d27	243.3	209.8	200.0	215.3	239.8	182.8	184.5	180.8	217.1	196.9	207.0
a28	373.5	283.8	241.0	324.0	363.0	332.0	255.5	321.4	305.6	318.0	311.8
d28	280.5	217.4	209.5	241.5	275.8	230.8	213.9	200.0	237.2	230.1	233.7
d29	282.5	218.8	237.5	255.0	345.0	245.0	273.8	200.0	248.4	265.9	257.2
d30	225.0	186.8	158.8	186.5	225.6	184.5	168.9	166.8	189.3	186.4	187.8
d31	190.0	123.8	133.8	131.3	157.5	148.8	138.8	118.8	144.7	140.9	142.8
d32	332.3	207.9	233.8	225.5	266.5	252.8	219.3	190.0	249.8	232.1	241.0
d33	262.5	171.5	172.8	175.8	271.0	215.8	199.0	161.5	195.6	211.8	203.7
d34	205.8	269.0	185.3	172.6	230.3	173.3	170.8	195.0	208.2	192.3	200.2
d35	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
d36	197.3	149.0	158.8	185.8	187.3	160.8	166.9	159.1	172.7	168.5	170.6
d37	275.8	230.8	225.0	213.3	256.0	191.3	222.4	220.3	236.2	222.5	229.3
d38	260.5	210.8	194.0	177.8	243.8	187.8	207.5	213.3	210.8	213.1	211.9
d39	357.0	289.0	209.5	351.6	286.3	260.4	235.5	218.6	301.8	250.2	276.0
b29	293.8	191.8	185.3	235.0	277.0	224.0	228.3	208.3	226.4	234.4	230.4
a30	213.3	149.5	147.6	177.5	198.3	166.0	166.0	156.8	172.0	171.8	171.9
b31	166.3	146.3	125.0	131.3	173.8	142.5	128.8	117.5	142.2	140.6	141.4
a32	225.1	157.8	145.8	165.8	199.0	187.5	202.0	135.0	173.6	180.9	177.2
b33	189.5	142.5	139.5	142.0	175.8	147.8	151.3	144.9	153.4	154.9	154.1
b34	238.8	166.3	192.5	203.8	197.4	200.0	202.5	180.0	200.3	195.0	197.6
b35	242.0	176.3	202.3	185.3	210.8	183.8	190.3	181.5	201.4	191.6	196.5
a36	178.0	132.0	130.8	141.0	177.3	145.0	139.0	118.5	145.4	144.9	145.2
b37	221.3	198.5	168.3	170.3	204.9	163.3	171.8	179.0	189.6	179.7	184.6
b38	202.8	159.5	168.8	165.8	215.0	187.5	166.0	174.3	174.2	185.7	179.9
a39	423.5	266.0	261.8	322.8	410.8	267.5	223.6	269.8	318.5	292.9	305.7
b40	251.6	157.8	175.0	174.8	192.8	174.9	199.8	180.5	189.8	187.0	188.4
b41	462.5	303.3	372.0	464.3	425.8	460.5	446.3	398.8	400.5	432.8	416.7
b42	206.0	134.8	129.3	151.5	191.5	157.8	171.0	119.5	155.4	159.9	157.7
b43	189.5	146.8	142.5	145.5	211.5	171.0	163.3	130.5	156.1	169.1	162.6

Table A4.11 Raw data for visual search task in main study. "B3" represents, for example, the mean search time binocularly in subtest 3; similarly, "MR" represents the mean monocular search time in subtest R. "BE" is the mean of all binocular search times and "ALL" is the mean of all search times.

ref.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
a01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
d01	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
b02	1	1	1	b	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
d02	0	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0
a03	1	0	0	0	0	0	0	1	2	0	1	2	0	0	0	0	0	0	0	0	0	0.	0
d03	1	1	0	0	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0	1	0	1	0
b04	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0
d04	0	1	1	0	0	1	0	1	2	0	0	0	1	0	0	0	0	0	0	0	0	1	0
a05	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0
d05	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	0	0	0	2	nd	nd	nd
b06	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	1	2	0	0	0
d06	0	1	1	b	0	0	0	0	0	0	1	1	0	0	1	1	0	0	0	0	0	1	0
a07	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1	0
d07	0	1	1	d	0	0	0	0	0	0	0	0	0	0	1	2	0	0	0	0	0	1	0
a08	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
d08	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	5	0	0	0	0	0	0	0
a09	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
d09	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0
b10	1	1	1	b	0	0	0	0	0	0	0	0	0	0	1	1	0	0	1	0	0	1	0
d10	0	0	0	0	0	0	1	0	0	0	0	0	1	0	1	3	0	0	0	1	0	0	0
b11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
d11	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0
b12	1	1	1	b	0	0	0	0	0	0	1	1	0	0	1	2	0	0	1	1	0	0	0
d12	0	1	1	0	0	0	0	0	0	0	2	3	0	0	1	4	0	0	0	0	0	1	0
a13	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1	1	0	0	0	2	0	0	1
d13	0	0	0	0	0	0	0	1	1	1	1	1	0	0	1	1	0	0	1	2	0	1	0
a14	0	1	0	0	0	0	0	1	1	0	0	0	1	0	1	1	0	0	0	0	0	1	0
d14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1	0	0	0
a15	1	0	0	0	0	0	0	1	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0
d15	1	1	1	0	0	0	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	1	0
a16	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	0	0	1
d16	0	1	0	0	0	0	0	0	0	0	0	0	1	0	1	5	0	0	1	1	0	0	0
a17	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0
d17	1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
b18	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
d18	0	1	1	b	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	2	0	1	0
b19	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
d19	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
b20	0	1	1	b	0	0	0	1	3	0	1	2	0	0.	1	1	1	0	0	0	1	0	0
d20	0	1	1	b	0	0	0	0	0	0	1	1	1	0	1	1	1	0	0	0	0	1	0
b21	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	.	.	.
d21	0	1	1	r	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
b22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0
d22	0	1	0	0	0	0	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0
a23	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	1	2	0	1	0
d23	0	1	0	0	0	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
b24	0	1	1	b	0	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	1	0	0

d24	0	1	0	0	0	0	1	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0
b25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0
d25	1	1	1	r	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0
a26	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0
d26	0	1	1	b	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0
b27	1	1	0	0	0	0	0	1	1	0	0	0	0	0	1	5	0	0	0	2	0	1	0
d27	0	1	1	b	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
a28	1	0	0	0	0	0	0	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	1
d28	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0
d29	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1	0	0	0
d30	1	1	1	b	0	0	0	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0
d31	0	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	2	0	0	0
d32	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	2	0	1	0
d33	0	1	1	r	0	0	0	0	0	0	0	0	1	0	1	3	0	0	0	1	0	1	0
d34	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	1	0
d35	0	1	1	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0
d36	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3	0	0	0	0	0	0	0
d37	0	1	1	r	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
d38	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
d39	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0
b29	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
a30	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
b31	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	0	1	0
a32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
b33	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	1	2	0	0	0
b34	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
b35	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
a36	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	2	0	0	0	0	0	0	0
b37	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
b38	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0
a39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	1	0
b40	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	0	0	0
b41	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3	0	0	0	0	0	0	0
b42	0	1	1	b	0	0	0	0	0	0	0	0	0	0	1	2	0	0	0	0	0	1	0
b43	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0

Table A4.12 Raw data for symptoms and history in main study. The numbers within the table follow the rules given in Table 7.3. The numbers along the top row represent the following:

1. masked paradigm
2. history of previous eye exam.
3. history of previous specs.
4. specs. used for distance/near/both
5. history of ocular pathology
6. history of binoc. vision problem
7. usual clarity of distance vision
8. frequency of distance blur
9. duration of distance blur
10. usual clarity of near vision
11. frequency of near blur
12. duration of near vision blur
13. incidence of diplopia
14. incidence of migraine
15. incidence of headache
16. frequency of headache
17. headaches with near vision
18. general health
19. medication
20. allergies
21. family history of binoc. vis. prob.
22. family history of migraine
23. family history of epilepsy.

APPENDIX 5
SUPPORTING PRESENTATIONS AND PUBLICATIONS

1. Evans, B.J.W. and Drasdo, N. (1990)
   Review of ophthalmic factors in dyslexia.
   Ophthalmic Physiol. Opt. **10**, 123-132.

2. Evans, B.J.W., Drasdo, N., and Richards, I.L. (1990)
   Optometric aspects of reading disability.
   Frontiers of vision. Transactions of British College of Optometrists 10th Anniversary Conference, Butterworths, London. pp. 14.

3. Evans, B.J.W. and Drasdo, N. (1991)
   Tinted lenses and related therapies for learning disabilities: a review.
   Ophthalmic Physiol. Opt. **11**, 206-217.

4. Evans, B.J.W., Richards, I.L., and Drasdo, N. (1991)
   Visual and Psychological Correlates of Dyslexia.
   Presented at: *Meeting the Challenge: the Second International Conference of the British Dyslexia Association*, Oxford.

5. Evans, B.J.W., Drasdo, N., Cook, A., and Richards, I.L. (1991)
   Pattern glare, tinted lenses, and reading performance.
   Presented at: *Coloured Spectacles and Reading Difficulties*, Apothecaries Hall, London.

6. Evans, B.J.W., Drasdo, N., and Richards, I.L. (1991)
   Optometric aspects of dyslexia - a controlled matched-group study.
   Presented at: *The Society of Experimental Optometry Annual Meeting*, Moseley, Birmingham.
   Ophthal. Physiol. Opt. **In Press.**

7. Evans, B.J.W., Drasdo, N., and Richards, I.L. (1991)
   Visual aspects of dyslexia - a controlled matched-group study.
   Presented at: *Reading and Reading Disorders: Interdisciplinary Perspectives. Rodin Remediation 18th Scientific Conference*, University of Bern, Switzerland.