

Vergence Eye Movements and Dyslexia.

by

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A thesis submitted for the degree of Doctor of Philosophy at the

University of Oxford.

Michaelmas Term, 1987

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Abstract

Vergence Eye Movements and Dyslexia.

Patricia Mary Riddell, St. Catherine's College, D.Phil. Thesis,

Michaelmas Term, 1987

Many theories have been proposed to explain why some otherwise intelligent children have unexpected problems with learning to read. In this thesis, evidence is presented in support of the hypothesis that one cause of such children's difficulties is failure to develop accurate vergence eye movement control. This leads to impaired ability to localise small targets reliably, thus explaining the 'visual' nature of some of these children's reading problems.

In 432 dyslexic and normal children vergence eye movements were recorded during the Dunlop Test of visual direction sense. Poor vergence eye movements were associated with variable ('unstable') responses in the Dunlop Test whilst good vergence control concorded with stable Dunlop Test responses. Further analysis showed that many dyslexic children were significantly impaired in several measures of vergence control when compared with either chronological or reading age matched controls. The parameters which distinguished most clearly between dyslexic and normal children's binocular control were found to be a target 1 degree of angular subtense moving at 0.6 degrees/second.

A computer game was also developed to measure the accuracy of children's spatial localisation and to compare this with the results of the Dunlop Test. Children with unstable responses in the Dunlop Test were significantly worse in this test than children with stable responses. Overall, females were poorer at this test than males, with unstable females registering the lowest scores. A difference between the percentage error rate in the left and right hemifields was also shown. Females with unstable Dunlop Test responses were poorer than stable females in both visual fields, while unstable males made more errors than their stable counterparts only in the left visual field. These results provide confirmation of the hypothesis that females are less highly lateralised for visuospatial functions than males.

A longitudinal study was carried out over 4 years on a cohort of 29 primary school children. The children were found to improve in the stability of their Dunlop Test responses, the stability of their vergence control and in their stereoacuity as they grew older. The children with unstable Dunlop Test responses and poor vergence control were found to be significantly worse readers than those who showed good binocular control. Also children who took longer to develop stable responses to the Dunlop Test had poorer reading ability than those who developed good binocular control at an early age.

The results are discussed in relation to a model of the development of reading ability and other postulated causes of reading difficulties. It is concluded that impaired vergence control may be associated with unreliable spatial localisation of words and letters. This is thought to be a sufficient cause for the difficulties some children show when learning to read, though it may often appear in combination with impaired linguistic skills.

Acknowledgements.

I would like to thank Professor Colin Blakemore for extending the facilities of the University Laboratory of Physiology to me during the time I have been studying at Oxford. I would also like to thank Miss Pauline Bagley and Mr Richard Welham for allowing me access to the facilities of the Orthoptic Department at the Royal Berkshire Hospital.

My thanks are also due to Dr. John Stein for providing me with a fascinating project, and for being available to assist me whenever I needed help.

Heartfelt thanks are due to both Sue Fowler, for her orthoptic expertise and the original idea, and to Doris Kelly for carrying out all the educational assessments on the children. They have also been excellent companions and have provided me with many new ideas in the course of discussions about the work.

During the past four years, we have visited several primary schools around Reading. I wish to acknowledge the co-operation I have received from the staff, pupils and parents involved. Without them, there would be no thesis.

To both the staff of the Orthoptic Department and the members of the Steinlab, past and present, I give my thanks for many fruitful, academic discussions and also light relief. I would also like to thank all the ophthalmologists at the Royal Berkshire Hospital who have been most co-operative in seeing the dyslexic children referred to the department.

I would like to thank the members of my house who have put up with me talking about nothing but dyslexia throughout the time I have been writing this thesis, and who have helped with the proof reading.

Finally, I would like to thank my parents, to whom this thesis is dedicated. They have provided much needed support, both emotional and financial. The added incentive of a holiday in Bermuda at the end of the day has given me strength in many dark moments.

'... two weeks ago another thing had happened. There had been an electric flash in his head behind his eyes, a feeling like a blinding blue-white glare for a second, and now he couldn't read anymore. It wasn't that he couldn't see. He saw clearly enough, but the words on a page swam and ran together and squirmed like snakes, and he couldn't make out what they said.'

John Steinbeck.
From: The Wayward Bus,
1947.

Chapter 1 - General Introduction

1.1 - Introduction

The first section of this chapter sets out the historical background to research on dyslexia. This is followed by an attempt to form a model of the possible routes from text to meaning through an analysis of the type of errors made by neurological patients who have acquired reading difficulties. A discussion of the development of reading ability in normal children is then presented. This is used as a basis for discussion of the potential sources of difficulty in learning to read and therefore the possible causes of developmental dyslexia. The problems of defining developmental dyslexia and of isolating children with this difficulty from within the normal population are also considered.

1.2 - Historical Background

Many terms are used to describe children who fail to learn to read despite adequate intelligence and educational opportunity. Word blindness, specific learning difficulties, strephosymbolia, and specific reading retardation are amongst these. Developmental dyslexia is perhaps the best known, and the most controversial.

The term 'dyslexia' comes from 'dys' meaning abnormal and 'legein' meaning to speak; and is used to describe a language difficulty: specifically, an impairment of written language. The first use of the word 'dyslexia' was made by Berlin in the 1870's. However, it was Hinshelwood (1895) who first described a developmental condition. He used the term 'word blindness', and defined it as:

'a congenital defect occurring in children with otherwise normal and undamaged brains, characterised by a disability in learning to read so great that it is manifestly due to a pathological condition and where attempts to teach the child by ordinary methods have failed.'

In his book, Hinshelwood (1917) described five case histories of

intelligent children who were unable to learn to read when taught by a method stressing visual routes. In four of the five cases, spelling was not affected, possibly since the method used to teach spelling was phonically based. The fifth child had been taught spelling by a purely visual method. Hinshelwood implicated a defect in the visual system as the prime cause of difficulties in these cases -

'It is thus in their failure to acquire the art of reading by sight alone and without appeal to any other cerebral centres than the visual that this defect becomes conspicuously manifest. They have been unable like other children to furnish their visual memory centre with the visual memories of words'.

He postulated that a hereditary maldevelopment of the angular gyrus in the dominant hemisphere might produce the type of symptoms described. This suggestion was derived from Dejerine's work on acquired dyslexia, in which lesions of the junction between the occipital and parietal lobes of the dominant hemisphere had been noted.

Orton (1937) preferred the term 'strephosymbolia' to describe the way in which children with reading difficulties mix up the letters in words. His research showed that many children with reading difficulties have problems in trying to sequence either visual information in space, or auditory information in time. Like Hinshelwood, Orton stressed the importance of the visual system, and of visual memory for spelling as well as reading -

'Spelling forms an almost insuperable obstacle to the strephosymbolic child. Since his memory of the word picture is not exact enough to serve as a basis for its recognition when seeing again as in attempting to read, it is not surprising to find that the much more accurate recall needed for reproduction also fails, and in greater degree.'

Although there is some agreement between Hinshelwood and Orton about the visual nature of the symptoms of reading difficulties, they did not agree about the cause. Orton discarded Hinshelwood's

hypothesis since neurological abnormalities of the angular gyrus were not found on autopsy in the high proportions that would be expected from the incidence of learning difficulties. He noted that reading difficulties were associated with stuttering and mixed handedness, that they ran in families, and were sex-linked. He suggested that a familial tendency to be indecisive over the controlling hemisphere was the cause of these difficulties.

The early history of investigations therefore shows that reading difficulties could arise from malfunctions of the developing visuomotor system. Although the early investigations pointed to clues provided by the symptoms of these children which could account for their reading difficulties, they were unable to establish the underlying cause. Studying the acquired dyslexias suggests a possible reason for this failure; i.e. that reading can be disrupted by breakdown of more than one system. Hence a search for a single unifying cause is unlikely to be successful.

1.3 - The Acquired Dyslexias

The study of lesions is an accepted technique used by neurologists and psychologists in order to determine the areas of the brain involved in controlling various mental processes. Patients with acquired dyslexia have been well studied. Oatley (1978: referenced in Morton & Patterson, 1980) points out that lesion studies are useful in providing information about the identity of components of behaviour. Paradoxically, they are less useful in providing accurate localisation of the neural structures responsible. Lesion studies help to elucidate the strategies used to interpret the written word, without being able to identify the neural substrate for these activities with any certainty. It must be remembered, also, that these

patients have deficiencies in their word processing abilities, so that the strategies they develop are not necessarily those used by the normal reader.

Impairment of the ability to read can develop as the result of a brain lesion caused by either injury or cerebral accident. In most of the cases in which reading is affected, the lesion has been found to include the area of the left parietal lobe, around the angular gyrus.

Some investigators have attempted to formalise the acquired dyslexias into a series of syndromes, each with specific qualifying error types. For instance, Marshall and Newcombe (1966) identify 'deep' dyslexia by the presence of semantic errors when reading single words. Although this approach offers the hope of identifying the areas of the brain responsible for specific syndromes, lesions resulting from stroke or injury are unlikely to respect anatomical boundaries. Moreover more than one area of injury may give rise to the same symptom. An alternative approach is to list the symptoms of each patient, some of which may or may not be similar to those identified in other individuals. It is then possible to discuss groups of patients with error patterns similar to those found in deep dyslexia without calling individual patients 'deep dyslexics'.

At least seven types of acquired dyslexia have been described (Ellis, 1984). These are characterised by the types of mistakes made by the patient (see table 1.1).

The errors made in each syndrome have been carefully analysed, and the results used to design a model of the pathways involved in reading (Ellis, 1984, see Figure 1.1).

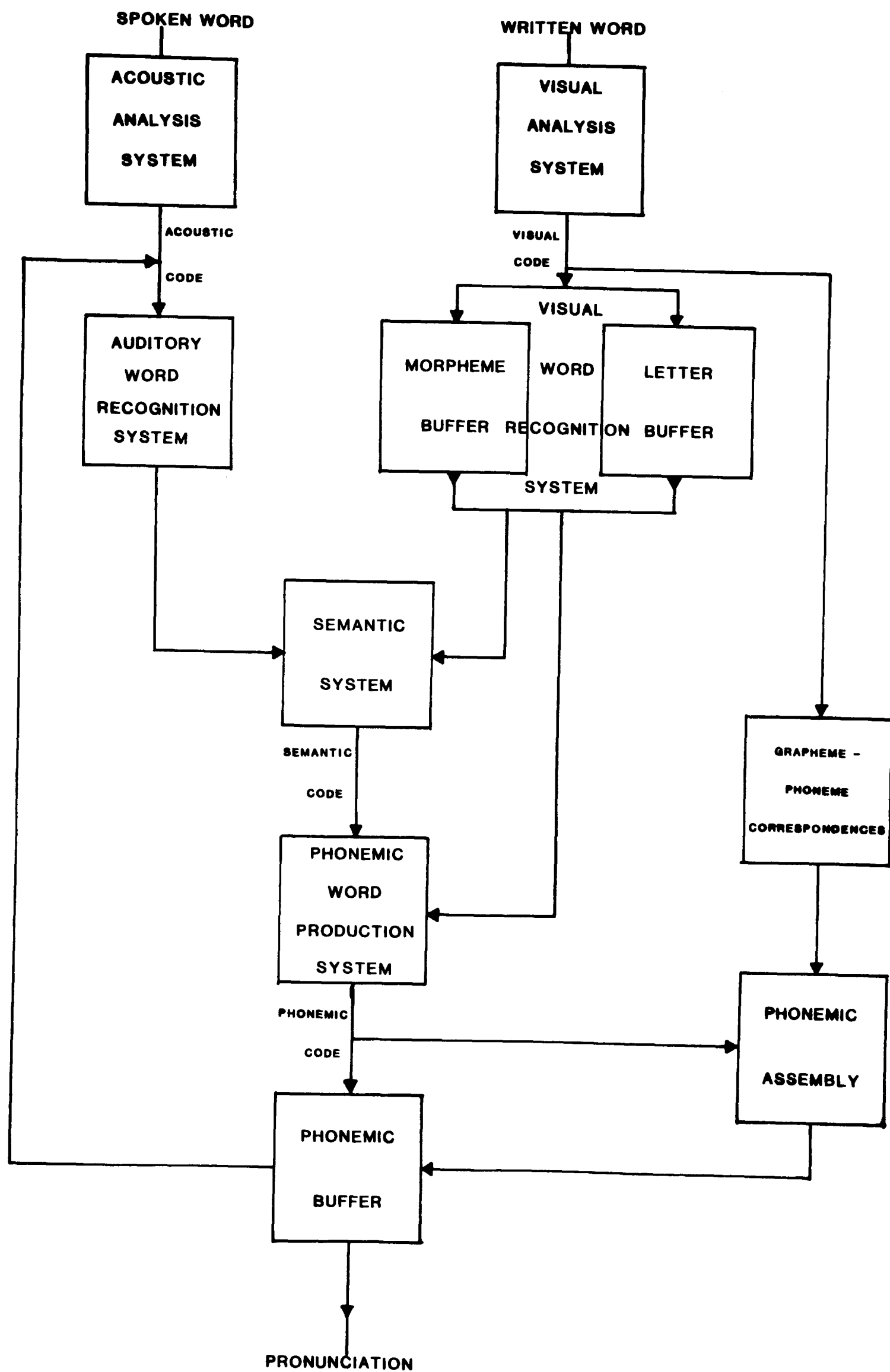


Figure 1.1 - Model of the reading process (from Ellis 1984).

Table 1.

Syndrome	Types of Error
Attentional Dyslexia	Visual segmentation errors
Letter by Letter Dyslexia	Read by first identifying individual letters
Visual Dyslexia	Can name component letters, but make visual errors when naming word
Phonological Dyslexia	Can read familiar real words, but cannot read simple non-words
Direct Dyslexia	Can read aloud, but show no evidence of comprehension
Surface Dyslexia	Can read regular words and non-words but cannot read irregular words
Deep Dyslexia	Semantic errors

This model is based on the logogen categorisation system first described by Morton (1969) on the basis of results reported by Marshall and Newcombe (1966). They pointed out that previous models of reading failed to account for the semantic errors found in deep dyslexia. These semantic errors (e.g. 'uncle' for 'nephew') showed that words may be recognised before meanings are attached. In the logogen system, auditory or visual analysis produces a code which is then recognised and assigned a meaning. The part of the model which performs the function of recognising words as patterns independent of their meaning is called the 'logogen' or 'word recognition' system.

Each of the pathways in the model can be shown to exist by analysis of the errors made by acquired dyslexics. It is necessary to postulate separate word recognition systems for the auditory and visual routes to meaning. This separation may be shown to exist by considering the results of experiments on 'facilitation'. In these experiments,

presentation of a spoken word did not increase the chance of recognition of the same word presented visually (referenced in Morton & Patterson, 1980). These results suggest that the identification of the stimuli was occurring in separate channels.

Two routes from the visual analysis system to the semantic system can be shown by comparing the errors in phonological dyslexia to those found in surface dyslexia. In phonological dyslexia the only words which can be recognised are those which are visually familiar to the patient. New words and non-words which require phonological processing cannot be read (Funnell, 1983). This kind of error has been explained by suggesting that the grapheme-phoneme correspondence route has been blocked; hence the patient has to recognise the whole word visually in order to be able to access the semantic code.

The characteristic errors made in surface dyslexia are evidence for the second route from visual analysis to the semantic code. In this condition simple irregular words which should be recognised visually are no longer accessible. However, the patients are capable of reading phonologically regular words and non-words (Coltheart, Masterson, Byng, Prior & Riddoch, 1983). Again the explanation lies in the proposal that two routes exist between the written word and the semantic system. In this case it is the direct visual recognition route which has been blocked (Coltheart et al, 1983).

The errors made in surface dyslexia also show that the grapheme-phoneme correspondence route accesses the semantic system via the acoustic code used by the auditory word recognition system. This is apparent from the mis-interpretation of homophones found in patients with surface dyslexia e.g. a patient who when asked to read the word 'listen' said 'Liston - the boxer' (Marshall & Newcombe 1973).

The symptoms of direct dyslexia show that it is possible to

disconnect the semantic system from both the direct visual route and the grapheme-phoneme correspondence route. Then neither route can access semantics, as is clearly demonstrated since words are identified but not understood.

Deep dyslexic errors show that common or irregular words are recognised visually before the semantic code is attached. This is demonstrated by the typical semantic error of the deep dyslexic. The first report of this error type is to be found in a case study prepared by Franz (1930, quoted in Marshall & Newcombe, 1980). He described a dyslexic patient who, on being shown the word 'cat' said 'mice'. This mis-interpretation suggests that the word had been recognised visually, but that the semantic code for that particular word was not accessible. Hence a semantically similar word was chosen.

It is known that common or irregular words can be recognised, not letter by letter, but from the overall shape of the component morphemes in practised readers. Two types of experimental evidence confirm this. The results of analysis of errors made during proof reading (Haber & Schindler, 1981) showed that errors were more easily detected when the shape of the word was altered. This would not be the case if the words were read on a letter-by-letter basis. Murrell and Morton (1971) then suggested from work on facilitation effects that the visual word recognition system was morpheme-based. They showed that visual recognition of the word 'sees' is enhanced by previous presentation of the word 'seen' but not by 'seed' which is visually similar but has a different morpheme base.

However, in letter-by-letter dyslexia, this faculty appears to be blocked. Patients without visual recognition of whole words nevertheless are able to build up a picture of the word by recognising its individual letters (Patterson & Kay, 1982). It seems that these

patients have access to a 'letter buffer' which allows them to store the individual letters of a word until they can add all the constituent letters. This condition suggests that two possible methods are available to the visual recognition system in order to identify words - a letter and a morpheme buffer.

In the model shown in Figure 1.1, one semantic system is thought to be sufficient for both visually and auditorily recognised words. Non-semantic dyslexia supplies indirect support for this. In this condition patients are able to read aloud both regular and irregular words, and also non-words, but they seem to have no comprehension of what they have just read. This would suggest that all routes to the semantic system have been blocked, or that the semantic system itself is damaged. If the auditory and visual systems had separate semantic systems, it would be possible to find dyslexics who could understand regular words but not irregular words, or vice versa. Since, in all cases so far described, access to the semantic system is blocked for all types of words simultaneously, this would suggest that a common semantic system is accessed by all routes.

Examination of the errors found in the acquired dyslexias has thus helped to build up a model of the possible ways in which visual language information can be processed. The description of the reading process includes a visual recognition system which can analyse words as wholes, or can break them down into graphemes, or even into single letters. The information processed in this way is then either recognised by the visual recognition system, or is converted to phonemes and assembled into a word which can be recognised by the auditory word recognition system. Both the auditory and the visual word recognition systems can access the same semantic code which allows the word to be identified and converted to a phonemic code (if

this has not already been produced by phonemic assembly). The phonemic buffer allows pronunciation of the written word.

One important point must be stressed again. Although a study of the acquired dyslexias allows us to see the possible routes available for reading, it does not allow us to assess which of these routes are commonly used. Acquired dyslexics attempting to understand the written word use strategies devised to overcome their particular difficulties. Hence these strategies may be found only in cases where the normal processes are no longer available. This means that great care must be taken when applying information gleaned from a study of the acquired dyslexias to reading processes used by normal readers.

1.4 - The Beginning Reader

The beginning reader is limited in the routes available between written words and pronunciation. No immediate visual recognition of words can take place, since s/he has not yet developed a visual memory for words, either through letter-by-letter reading or as wholes. Words have to be identified by their acoustic code by accessing the semantic system in the same way as the spoken word. Hence, the beginning reader is very like the surface dyslexic, who has no access to words via their visual pattern, but can recognise words only after production of an acoustic code.

There are two routes from the visual analysis system to the auditory word recognition system. The first of these routes is the recognition of words as wholes by rote learning, thus training the visual recognition system to identify the word. The visual word recognition system can then access a phonemic code via the phonemic word production system. This phonemic code is used to produce an acoustic code through which the child identifies the meaning of the

word. This is the route employed by teachers using the 'look-and-say' method. The second route is to access acoustic code by training the child to build the word up from its component graphemes. This method of teaching is used in phonic based programmes.

New readers can be taught by either of these methods since the words they will come across will be both visually and auditorily simple. However, some words in the English language have irregular grapheme-phoneme correspondences, and so have to be taught by a purely visual method. It must also be noted that children cannot learn to read efficiently by purely visual methods. This method of reading gives the child no means to decipher new words for himself. This can only be achieved by teaching the child the relationship between the letter shapes and their sounds, as in phonic methods of teaching. The best schemes for teaching children to learn to read, therefore, probably consist of a mixture of both of these methods.

The early reader can also use reading by context to guess at the words he sees. In the early stages, the words guessed may bear no visual resemblance to the word on the page, but as the child is taught the skills of grapheme-phoneme correspondence, the word guessed becomes more visually similar. This transition may start with the child identifying the beginning letter of the word to be read, and therefore guessing at a word which begins in the same way as the word on the page. As the child's skills develop, however, contextual guessing becomes more accurate.

The child may also be learning how to split words up into their component graphemes, to associate these graphemes with the appropriate phonemes, and then to blend the constituent sounds to produce the word. As the child acquires (or is taught) this method of word attack, s/he moves away from contextual guessing. The errors made by children

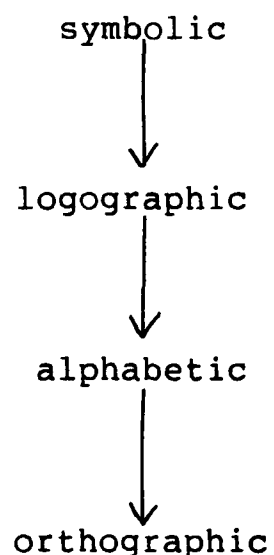
at this time are mostly for irregular words which cannot be read by grapheme-phoneme correspondence rules, or mis-identification of visually similar words (Marcel, 1980). This is like the pattern of errors described in surface dyslexia.

Bryant and Goswami (In Press) have shown that, even in the early stages of reading, children can use analogy as a guide to the pronunciation of words. Thus, a child who has learnt the word 'cat' is more likely to be able to read 'bat' or 'mat' correctly even though they have never seen these words before.

Thus, there are at least four strategies available to the beginning reader:

- 1) Whole word recognition.
- 2) Contextual guessing.
- 3) Grapheme-phoneme correspondence rules.
- 4) Reading by analogy.

Frith (1985) has produced a developmental model to account for the manner in which normal children acquire reading and writing skills. In this model, there are four stages in the acquisition of 'automatised' reading and writing:



In the first 'symbolic' phase of development, children come to appreciate the nature of print as a means of symbolising ideas. From this point they can learn to use the main features of commonly occurring words to identify them. This is similar to the whole word recognition phase described above. In Frith's example, a child might recognise the sign for McDonald's by the large yellow 'M' at the start of the word long before the child is able to decipher the whole word either visually or phonologically. This 'approximate visual recall' becomes more accurate as the child builds up a sight vocabulary, until the child is able to write words down. The first attempts at writing may therefore show many spelling errors of a visual nature. At this point, Frith suggests that there is a dichotomy in the use of strategies. The reading process continues to develop by use of visual recognition of words. However, this strategy is found to be unsuitable for the correct spelling of words. The child's visual appreciation of the word is frequently somewhat inaccurate, hence words are spelled incorrectly. As a result, the child begins to learn an 'alphabetic' approach to spelling equivalent to the phoneme-grapheme correspondence phase described above. Writing is sequential and is therefore accessible to a process of breaking words down into their component sounds. Hence, Frith suggests, the first use of phonology is not in reading but in spelling. At this point, a child may recognise an irregular word correctly, but will spell the word phonologically, thus producing typical kinds of spelling error.

If the child is encouraged to follow the phonological approach to writing, this method could become potentially available also for the reading process. At this point the child will learn to pronounce new words on his own by accessing the sound components of the individual letters of the word. The final stage of the reading and writing

process is reached when the child automatically recognises segments of words without having to sound them out. At this stage new words can be read by analogy with words, or word segments, already stored in the visual lexicon. This is termed the 'orthographic' stage of reading and writing.

Frith's scheme is useful not only in its ability to model the acquisition of literacy skills in children, but also as a means of predicting why some children fail to learn to read. It does not, however, incorporate the ability to use contextual guessing or analogy with other words which the child has already learnt in order to read or spell unknown words. Contextual guessing is likely to take place during the logographic phase of Frith's model, when children have only approximate visual cues to guide their reading attempts. The use of analogy with already known words is likely to be used both in the logographic phase and in the alphabetic phase. This is because this method of word analysis is accessible to both the sounds of words and to the visual appearance of words. Children will be able to guess that a word which sounds similar to a known word might be spelt similarly. In the same way, two words which look similar might be expected to have the same pronunciation. Hence this technique can be used for both the reading and the spelling processes.

A complete model of the development of reading and spelling processes, therefore includes the basic visual and phonological routes available to the beginning reader, but also considers the higher cognitive functions that even the beginning reader can bring to bear on the learning process.

Some of the most widely held theories of why some children show developmental disability in literacy are discussed in the next section.

1.5 - Developmental Dyslexia

The work of Hinshelwood (1917) showed that dyslexia could be found in some otherwise educationally normal, intelligent children. There is, now, little dispute that a group of children exists who have specific problems with the acquisition of literacy skills - 'developmental dyslexics'. This section reviews the research into possible reasons for this failure to learn to read. All references to dyslexia below are therefore, by implication, to developmental cases, unless otherwise stated.

Do these children form a discrete group or are their difficulties described adequately by the lower end of a continuum which ranges from exceptionally good readers to exceptionally poor readers? This question can be investigated by considering the prevalence of dyslexia in the normal school population.

1.5.1- Prevalence of Dyslexia

Since there is disagreement in the literature about the definition of dyslexia and the proportion of dyslexics in the normal population, it is necessary to use very strict criteria for choosing groups of children with reading disabilities for research purposes. All possible secondary causes of dyslexia must be excluded to ensure that the population contains purely reading disabled children. The World Federation of Neurology definition of dyslexia can be used in these situations to provide exclusionary criteria. This definition states that 'specific developmental dyslexia' can be defined as:

'a disorder manifested by difficulty in learning to read despite conventional instruction, adequate intelligence and sociocultural opportunity.' (Critchley, 1970).

From this children who have been absent from school for long

periods due to illness, or who have had many changes in teacher or school, and therefore may have suffered educationally, should be excluded from dyslexic samples. Children from low socioeconomic backgrounds or from different cultural backgrounds should also be excluded. A basic level of intelligence should be used as a criterion for choosing samples of dyslexic children. Control groups used for comparison with dyslexic groups should be chosen using the same criteria.

This is not to say that only children who have had adequate schooling, who are of an adequate intelligence and, especially, who are middle class, can be dyslexic. A different set of criteria can be used for situations in which educational or medical intervention is indicated, thus ensuring that all children in need of assistance are helped. However, in research situations it is more important to have a sample group which is uncontaminated by children with secondary problems than to have a politically 'fair' definition of developmental dyslexia.

The first problem encountered in studies investigating the occurrence of children with reading problems in the normal population is how to define these problems. Reading difficulties can be caused by low intelligence, lack of educational opportunity and other causes. Children with specific reading difficulties have to be differentiated from children who have reading difficulties attributable to lack of intelligence.

The first attempts at measurements of this sort were based on an accomplishment quota, measured by taking the ratio of actual reading age to mental age. This was thought to give a quantitative measure of how far behind or ahead of a child's potential for reading that child was performing. A similar type of measurement was made by comparing

general ability and achievement on a percentile scale. A cut off point was defined on the basis of the difference between reading performance and ability. Children with reading scores below this were then considered to have specific reading problems.

Both of these measures fail on statistical grounds (Rodgers, 1983). They both lead to biassing of the sample towards reading disabled children with higher mean ability scores than the over-achievers with whom they are compared. This happens because children with low ability are unlikely to fall far enough behind in their reading attainment to be considered dyslexic. In order to prevent such biassing, it is necessary to calculate a regression of attainment scores against ability scores for the population on which the investigation is to be carried out. This equation will be sensitive to the different ranges of reading abilities possible at each level of attainment and can also control for the age of the children under examination (Rodgers, 1983).

This type of analysis was performed for 5 different populations by Rutter and Yule (1975). They wished to test the hypothesis that the children with specific reading retardation were part of a continuum of reading ability. They calculated from the regression equation that 2.28% of children would be expected to fall two or more standard deviations behind the level predicted for their ability. When they measured the proportion of children actually falling into this category, they found that it was significantly larger than the 2.28% predicted. The discrepancy was larger in London than it was in the Isle of Wight (9.26% in London versus 3.61% in the Isle of Wight). They suggested that this 'hump' was indicative of a group of children with severe and specific reading retardation which was not part of the continuum of reading abilities. The children who formed the 'hump' at the lower end of the reading abilities scale were different from the

rest of the population in many other respects. There were many more boys in the reading retarded group and many of these were found to have had delays in speech and language. When their reading progress over 4-5 years was compared to children who had reading difficulties associated with low IQ, unexpectedly they were found to improve less than the generally backward children. Hence, both on statistical grounds, and on the evidence of other linking factors, a group of children with specific reading retardation was proposed.

This study has been criticised by Rodgers (1983). He expressed caution about these findings on three grounds:-

1) The reading tests used by Rutter and Yule had a ceiling value of around 12 years which was reached by some of the children tested. This ceiling effect could have biased the linearity of their regression equation thus undermining the subsequent analysis.

2) The 'hump' at the lower end of the Gaussian distribution presented by Rutter and Yule might equally well be explained in terms of a negatively-skewed distribution.

3) The prevalence of specific reading retardation varied with the reading test used to define the population. This could again be explained by floor and ceiling effects in these tests.

In this paper, Rodgers (1983) reports the results of a cohort study of over 8,000 children born during the same week in April 1970. These children were followed up 10 years later. During the follow-up, tests were administered in order to calculate the proportion of children with specific reading retardation. The ability tests used were four sub-tests taken from the British Ability Scales (Word Definitions, Recall of Digits, Similarities and Matrices). A shortened Edinburgh reading test was used to assess reading ability. A regression of BAS score on reading score was performed on the population. Again, 2.28%

of children would be expected to have reading ability more than two standard deviations behind their ability. The actual percentage of children who were found to fall into this category was 2.29% which did not differ significantly from the expected value. From these results Rodgers concluded that the specific reading retarded population form the lower end of a normally distributed profile of ability within the reading disabled population. He concluded that Rutter and Yule's results are explained by the ceiling effects of the reading tests administered. If this is true, estimates of the proportion of reading disabled children in a population will depend only on the cut-off used to define reading disability. This should always be stated in any research dealing with reading disabled populations.

There are several problems with the work presented by Rodgers. Firstly, the normative curves for the BAS are based on the results of tests performed on a cohort of children which included some dyslexics. The standardisation procedure used to produce the norms presumes that the population from which the data has been collected is normally distributed. If dyslexic children do perform significantly worse than normal readers in some sub-tests as a result of their reading difficulty, then including their results when calculating normative curves will reduce the mean score for that test. When these normative curves are then used to determine whether children are performing at a level expected for their age, only children who perform particularly poorly will be considered abnormal. Hence, the number of children found to be dyslexic in any population will be reduced. It is necessary to ensure either that the tests being used to define the dyslexic population do not disadvantage the dyslexics being tested, or that the normative curves are produced using a population of children who have normally distributed reading abilities.

Secondly, if the specific reading retarded population were only the lower end of a continuum there would be no reason why so many of this population turned out to be male. Since Rodgers did not give distribution curves for each sex, the possibility that there was a hump at the lower end of the curve calculated for males alone was not tested. This might be balanced by a hump at the higher end of the curve produced using the values obtained from the female population. Is there something specific about the reading process which predisposes more males than females to failure? If this is the case, then the population who are found to have specific difficulties with reading may be separable from the rest of the population on grounds other than their reading difficulty per se. As yet, no explanation for the preponderance of males in the reading disabled population has been substantiated experimentally.

1.5.2 - Types of Dyslexia

The process of learning to read involves many skills. Language is first heard and then vocalised. Thus, when children begin to learn to read they recognise the meanings of words they have heard and used in speech. Any impairment of hearing or of speech processes might therefore be expected to result in reading difficulties. Reading involves vision and visuomotor processes since the words have to be perceived before meaning can be attached. Short term memory is required to remember sequences of letters in words and words in sentences. Long term memory is also required to recognise words on their next presentation. Correct sequencing is required so that the letters in words are viewed and the sounds in words heard and remembered in the correct order. A deficit in any one of these or other skills required in reading may result in difficulties in

learning to read.

This has led to many lines of research into reading difficulties. Some workers have proposed one unifying theory for all reading difficulties, while others have been less ambitious and have postulated that reading difficulties can be attributed to a number of different causes. These theories of dyslexia can be roughly divided into phonological, linguistic, intersensory integration, short term memory, cerebral lateralisation and visuospatial categories.

Bryant and Bradley (1985) suggest that three types of experimental evidence are required in order to show a causal relationship between two events. These are:-

- 1) A larger proportion of the reading disabled population must be affected by the developmental deficit than the control population. The control population should be matched not only for age but preferably for reading experience as well. Hence they provide both chronological and reading age matched controls in their studies. This allows the amount of reading experience to be discounted as a variable when analysing the results of the experiment.

- 2) The developmental deficit should be capable of predicting those children who will later experience reading difficulties. Thus in longitudinal studies, the deficit measured in one year should predict children with reading deficits in future years.

- 3) Training which alleviates the developmental deficit should also improve reading ability.

Unfortunately, most of the research into possible deficits in reading disabled children have not followed these guidelines. The most common failings are a lack of a reading age matched control group and inadequate descriptions of the manner in which the reading problem has been assessed. This makes it difficult to make comparisons between the

work of different research groups. In the following sections various theories will be reviewed.

1.5.3 - Phonological Theories

Much research has been directed towards the investigation of the links between the ability to segment words into their component phonemes and reading ability in beginning readers. This ability is required in Frith's alphabetic stage of reading (Frith, 1985). Failure to acquire this skill might delay beginning readers in the logographic phase of the reading process. Bryant and Bradley (1978, 1983, 1984, 1985) have provided much of the evidence for this theory.

Bryant and Bradley (1985) have presented three forms of experimental evidence to show that reading disabled children find difficulty in splitting words up into their component phonemes. First, they assessed children for their ability to identify rhymes and alliterations for simple words. In this experiment a group of reading disabled children (average age - 10yrs 4mths) were compared with a group of reading age matched controls (average age - 6yrs 10mths). The reading disabled children were found to score lower on both the test of rhyming and of alliteration when the words were presented orally. This shows that there is a deficit in the ability to identify rhymes and alliterations in a reading disabled population.

The second type of experimental evidence is supplied by the results of their longitudinal study of 400 four to five year olds. This was commenced when the children were first starting school and had no reading experience whatsoever. It finished four years later when the children were eight to nine years old. Tests of rhyme and alliteration were given to the children at the start of the study and tests of reading, spelling and maths ability were given at the end. From this,

the ability to rhyme at a pre-school age was found to be a good predictor of average reading ability three to four years later. There was no predictive effect of rhyming for the scores in the maths test. This result suggests a causal link between a deficit in a child's ability to segment phonemes (a skill vital for the task of rhyming and alliteration) and reading disability. However, the result could also be explained in terms of a factor which affects both reading ability and phonemic segmentation. In order to discount this possibility it was necessary to show that training in phonemic segmentation caused an increase in reading ability.

In the third set of experiments, Bryant and Bradley (1985) split 65 six year old children into four groups three of which were given identical amounts of teaching of different types. The first group received training in rhyme and alliteration by categorising pictures by the sounds of the words. The second group were treated in the same way at the start of the study, but were given training on rhyme and alliteration using plastic letters in the second year. The other two groups formed controls: one group had training in categorising pictures in semantically related sets. The final group had no training at all. At the end of two years, all children were given tests of reading and spelling. The children whose teaching strategies included rhyming and alliteration improved their reading ability significantly more than those who had no such training. Hence the results of the extensive tests on phonemic segmentation abilities in the reading disabled population suggest a causal link between this skill and reading ability in children.

However, the results of these experiments are not as strong as they at first appear. In the predictive longitudinal study, only the average reading ability is predicted by the initial scores on rhyme

and alliteration tests. Bryant and Bradley also state that when the results were examined on an individual basis, only 25% of the poor readers at eight years old would have been predicted on the basis of their rhyming and alliteration scores. Also, there were some children who scored poorly on the initial test who nevertheless went on to become good readers. Hence there was no one-to-one correspondence between poor phonemic segmentation and reading disability.

The second problem with the results presented above is that, in the training study, the children whose reading age improved most significantly were those who had received both training in rhyme and alliteration and in dealing with words with both visual and tactile cues. The additional improvement in this group could therefore be due to the training in more than one domain.

These results suggest that other skills could be disrupted in some children with reading disability. This does not detract from Bryant and Bradley's primary finding that there is a deficit in the ability to segment phonemes in some reading disabled children. It does, however, imply that additional causes for reading disability might be found.

Additional evidence for difficulties in phonological processing has been described by other workers. Snowling (1981) showed that children with dyslexia were poorer than reading age matched controls on a task which required them to repeat words. Two types of words were used - real words and closely similar nonsense words. The reading disabled children were found to have trouble only with the long nonsense words but not with closely similar real words. This suggests that there is a problem with phonological processing only when stimuli are unfamiliar.

In a very simple experiment, Snowling and Frith (1981) gave a group of dyslexic children (aged 10 to 12 years) and a group of normal

children matched for reading age (aged 8 to 10 years) a list including regular, irregular and nonsense words to read. A clear difference appeared between groups in the number of nonsense words they could read. The reading disabled group were far less successful than the normal readers of the same reading level. Both groups found regular words easier to read than irregular words, but the difference for regular word types between the reading disabled group and the normal group was smaller.

There are at least two possible explanations for these results. First, the good readers may be better than the poor readers at phonemic segmentation. This would affect nonsense words more than regular words since a visual recognition approach would be successful for common regular words but not for nonsense words.

The results could also be interpreted as showing an impairment in visual processing. The reading disabled group may be unable to remember the correct order for letters in words. Guessing the word would be more successful for a common word than for a nonsense word which might be guessed as a real word. Hence the greater difference between normal and disabled readers would be for nonsense words.

The results of Snowling's 1981 experiment show that phonological processing difficulties alone can result in deficient processing of nonsense words. In these experiments, the words were presented aurally and the children were required to make a vocal response. Hence there was no visual processing to confuse interpretation of the results. These findings do not, however, answer the question of whether visual errors may disrupt the processing of nonsense words. Either or both phonological and visual mechanisms might be found to be disrupted in a population of reading disabled children. Careful examination of error

types would be helpful in distinguishing between different processing deficits.

Mann (1987) provides evidence that some children with reading difficulties have problems when segmenting words into their syllabic components. Good readers were found to be better than children reading at the level expected for their age on a task which required the children to clap out the number of syllables in a word (e.g. to-gether would require three claps). Both the good and the normal readers were significantly better than dyslexic children on this task. The words were presented to the children orally so that again there was no possibility of visual interference in the task. These results, however, only show that the skill is positively correlated with reading ability. It is not possible to tell from the results whether the children who were good readers had acquired this skill through their experience with print or whether the skill was a prerequisite of good reading ability.

The evidence presented here suggests that some children have difficulty in learning to read as a result of deficient phonemic segmentation skills. These children are therefore unable to move from the logographic phase to the alphabetic phase of the reading process as described by Frith (1985).

1.5.4 - Linguistic Theories

One of the main proponents of the linguistic theory of dyslexia is Vellutino. In a recent review (Vellutino, 1987) he defined dyslexia as:

'a subtle language deficiency. The deficiency has its roots in other areas: phonological-coding deficits; deficient phonemic segmentation; poor vocabulary development, and trouble discriminating grammatical and syntactic differences among words and sentences.'

Some of these difficulties relate to processes resulting in the orthographic phase of reading described in the Frith's developmental model. Higher order cognitive processing skills will be involved in the acquisition of the skills needed to produce grammatically and syntactically correct sentences. The phonemic coding and segmentation difficulties have been described above, and are widely accepted as being a causal factor in many children's reading difficulties.

An inadequacy in verbal language would make it more difficult to acquire proficiency in written language. This might be associated with vocabulary deficits in children with oral language problems or with pronunciation deficits. Thus children with articulation difficulties exhibit increased difficulties with the concept of phonemic segmentation.

Several post hoc studies have compared the incidence of linguistic deficiencies in normal and dyslexic populations. Ingram and co-workers (Ingram and Reid, 1956; Ingram, Mason and Blackburn, 1970) showed that approximately half of children referred to a clinic for reading difficulties had a history of speech and language difficulties. Waugh and Norman (1965) showed that poor readers performed less well on tests of auditory memory than normal readers only if the auditory material tested had a linguistic component.

Snowling (1987) describes the spelling errors made by children with various deficits in their phonological abilities. A child who could not differentiate some sounds and thus had difficulties at the input stage, was found to have severe spelling difficulties. She was unable to write down even the first phoneme of a word correctly, and often started her spelling attempts with the last heard phoneme. A child with phonemic segmentation and verbal memory deficits was found to attempt correctly the beginnings of words, but to make most of her

spelling errors at the ends of the words. This was especially true of long words, suggesting that her verbal memory deficit made these particularly difficult. Finally, a child with deficits of articulation, i.e. at the output stage, was found to have particular difficulties when spelling words which he could not pronounce. This might suggest that the nature of the phonological processing difficulty is important in determining the nature of the spelling errors made by dyslexic children. This idea is supported by the work of Bishop (1985) who has shown that children with dysarthria, who are incapable of controlling their vocal apparatus due to brain damage, are nevertheless good spellers. On the other hand, Robinson, Beresford and Dodd (1982) showed that children with no spasticity, but who were unintelligible, were poor spellers.

Denckla and Rudel (1976) showed that poor readers took significantly longer than normal readers to name common objects, letters, colours, words and numerals. The poor readers also made more errors in naming common objects from pictures. This data would suggest that some dyslexics have a deficit in word retrieval.

Studies by Fry (1967) and Schulte (1967) (reported by Vellutino, 1987) suggest that normal readers of seven years of age have larger speaking vocabularies and greater verbal fluency than poor readers of the same age group. Vellutino (1979) points out that this deficit may well be independent of reading experience since the children tested were only in second year of primary schooling and so had had little experience of complex vocabulary or sentence structure in their reading material.

Nevertheless none of the studies reviewed above prove a causal link between deficits in oral language attainment (either in terms of vocabulary or articulatory problems) and reading disability since the

guidelines set by Bryant and Bradley have not been satisfied. More stringent experiments are required before it is possible to tell whether the suggested correlation between children's oral language difficulties and their reading disabilities is causal.

1.5.5 - Intersensory Integration

Birch and Belmont (1964) suggested that retarded readers may have difficulties not in primary sensory processing, but in the associations between sensory functions. Thus, they suggested that children who were unable to integrate information from the visual system with information from the auditory system would be poorer readers than children who performed this task successfully. This skill would be required in transferring from the logographic to alphabetic phases of the developmental reading process. The alphabetic phase of reading requires the association of visual stimuli (graphemes) with their auditory equivalents (phonemes); hence the importance of intersensory integration.

In order to test this hypothesis, they compared the ability of 150 backward readers with 50 normal readers of the same ages (9 to 10 years old). The children were tested on their ability to match auditory patterns consisting of short and long taps with visual patterns of short and long bars. The children listened to the auditory patterns then chose a matching visual pattern from a multi-choice array. The results of this experiment showed that, even when intelligence was accounted for, the poor readers were less proficient at this test than the good readers. From this, Birch and Belmont concluded that the poor readers were less able to make reliable associations between auditory and visual information than normal readers, and that this may have had some effect on reading competence.

There are many other ways of explaining these results however. In this experiment, the children were not tested on their ability to correctly hear the auditory pattern or correctly identify the visual pattern, so a primary sensory deficit was not ruled out. The effects of both visual and auditory short term memory were also ignored. Moreover, the assumption that the correlation between the result and a reading deficit shows a causal link is also disputable. The result may show that children who fail to gain experience in combining visual and auditory information because of a failure to learn to read efficiently are therefore poorer at combining these types of information in other situations. Hence cause and effect are not differentiated.

1.5.6 - Short Term Memory Deficits

Miles (1983) reviews his theory, developed with his co-workers, that dyslexia is a result of 'a failure to retain complex information over time'. The first evidence for this theory came from studies comparing normal and disabled readers using a test of visual memory for digits. The subjects were shown strings of 5, 6 or 7 digits, and the time of presentation required to allow correct identification of the string was measured. These results showed that reading disabled persons of all ages took longer to respond correctly than controls (Miles and Wheeler, 1974), thus suggesting a deficiency in the processes of registering, transforming, coding and/or storing sensory information.

The effects of such deficiencies on reading ability were considered in terms of the internal lexicon required to store information about the verbal, semantic and written identities of words. This lexicon is thought to be stunted in the reading disabled person both in terms of the length of time and number of presentations required before an

entry is successfully stored or later retrieved. The experiments of Denckla and Rudel (1976) in which reading disabled children were shown to be less proficient at naming colours is interpreted as reflecting this difficulty in retrieving items from memory. The reading disabled child's memory is postulated to become easily overloaded, thus explaining the difficulties with recall of digits. Miles also postulates that the dyslexic child is less able to 'tag' the correct names onto concepts which are not easily distinguished. This is used to explain the confusion of 'b' and 'd', and 'left' and 'right'. Miles concludes that:

'if one postulates a faulty system of information processing which affects the functioning of the lexicon, then all or most of the difficulties experienced by dyslexic subjects can be brought under the same explanatory principle.'

Miles then attempted to show a relationship between reading and/or spelling ability and scores on tests which require information processing. Seven tests were investigated:- 1) repeating digits presented orally in the reverse direction; 2) identifying left and right both with respect to the subject and with respect to the examiner sitting opposite; 3) repeating polysyllabic words; 4) subtraction; 5) saying tables; 6) saying the months of the year in order; and 7) saying the months of the year in reverse order. Normal subjects of all ages were found to make fewer errors on these tests than reading disabled subjects matched by age. From this, Miles concludes that these tests are useful indicators of the presence of dyslexia.

There are at least two major criticisms that can be made of this research. First, the controls used were matched for chronological age, not reading age. This type of matching does not control for the effects of reading experience on the skills being tested. Secondly, all the tests used seem to have been chosen arbitrarily and involve

more skills than memory alone. It is possible that some children will fail on a subset of these tests as a result of some other sensory or motor impairment. To attribute all dyslexic failing to difficulties in short term memory overlooks this possibility.

1.5.7 - Cerebral Lateralisation

Spoken language is known to be controlled by the left hemisphere in most right-handed people. Anatomical asymmetries have been found in some areas of the brain which have been associated with language functions. Geschwind and Levitsky (1968) found that 64% of a sample of 100 adult brains examined at post mortem showed a larger planum temporale on the left side. In 25% the areas of the right and left planum temporale were equal; and in only 11% the pattern was reversed. The planum temporale lies next to the primary auditory cortex. This area on the left side of most humans is known as Wernicke's area, an area with known language reception functions. Eidelberg and Galaburda (1984) looked at the inferior parietal lobes in nine humans. Since the left inferior parietal lobe is also associated with language function, they suggested that any asymmetries in this area should reflect the asymmetry found in the planum temporale. Asymmetry of the area PG, in the angular gyrus, was confirmed in approximately two-thirds of brains, and this correlated significantly with the asymmetry found in the planum temporale. In this study, Eidelberg and Galaburda (1984) also showed that the area PEG in the right parietal lobe was larger than that on the left. This reversed asymmetry was explained by postulating a visuospatial function for this area. These investigations suggest that, contrary to past beliefs, there may be anatomical correlates for the superiority of the left hemisphere for language and of the right hemisphere for visuospatial tasks. This will

only be true if prescribing a larger area of cortex enhances the ability of an area to perform a given function.

One dominant language centre is required for the motoric control of speech. Hence all language functions, including reading and writing, might also be confined to the left hemisphere. Some language difficulties, for instance developmental dyslexia, might arise therefore from language being abnormally distributed in both hemispheres. This was postulated as a possible cause for dyslexia by Geschwind and Galaburda (1987).

In order to investigate the possibility that there is a connection between incomplete cerebral dominance and dyslexia, the brains of known developmental dyslexics have been studied at autopsy. Drake (1968) was the first to report the neuropathology of such a brain. He found excessive numbers of displaced neurones in the subcortical white matter, especially in the parietal lobe. No differences between left and right sides were reported, however. Galaburda and Kemper (1979) reported a second case in which they looked specifically for differences in structure in the two hemispheres. The abnormalities they found were restricted to the left hemisphere. These consisted of micropolygyria, dysplasias and ectopias. Abnormalities were limited to specific parts of the left hemisphere including the planum temporale. In a third case (Galaburda, 1983), the abnormalities were more common in the left hemisphere but some were found also in the right parietal cortex. Preliminary investigations of two other brains (Galaburda, Sherman & Rosen, 1985) also showed abnormalities most often in the left temporal lobe. In all the brains so far investigated the sizes of the plana temporale on the two sides were equal. Many of the dyslexics whose brains have been autopsied so far have had histories of language delay, and so would be categorised as audiophonological dyslexics.

It has commonly been held that minor neurological defects of the sort described above have little bearing on cortical function, since they are frequently found in reputedly normal brains. However, the educational status of people whose brains are autopsied is seldom known. Hence it is impossible to determine for certain whether the lesions found did have any functional significance. This information will only be forthcoming when a large number of brains from people with a documented educational background have been compared with those from known dyslexics. Until such information is forthcoming, speculation will be rife.

Geschwind and Galaburda (1987) have proposed a comprehensive theory which might account for many of the developmental dyslexias. The higher incidence of developmental dyslexia among males has been frequently reported. Geschwind and Behan (1982) also produced some evidence to suggest that dyslexia is more common among strong left-handers. Schacter and Galaburda (in press) included all non-right handers from a group of 1000 professionals measured using the Oldfield Handedness Battery. This included anyone who reported using their left hand for more than one task consistently or in at least 5 tasks intermittently. In this population, the incidence of dyslexia was found to be 9%. This was the same as the percentage of left handers with dyslexia. In the fully right-handed population the incidence of dyslexia was said to be significantly lower (3%). Geschwind and Galaburda (1987) therefore suggest that the influences which affect handedness might also be instrumental in causing developmental dyslexia, at least in extreme cases.

Sex hormones are proposed as the common factor linking dyslexia to higher incidence of left handedness. In order also to account for the higher incidence of dyslexia in males, the male sex hormone,

testosterone, is postulated to be the major contributor. Both male and female fetuses are exposed to maternal testosterone. Hence both males and females have some chance of being affected. However, the male fetus is also exposed to testosterone produced by the developing testes. This might suggest that any females affected will show less severe deficits than affected males since the levels of testosterone that females are subjected to are smaller. However, the effect of any testosterone present in the foetal blood will also be controlled by the sensitivity of the fetus to this hormone. Hence, although females are subjected to lower overall levels of testosterone, the effects of any testosterone present may be strong if they are particularly sensitive to it.

The adult pattern of larger language areas of the left hemisphere is also found in foetal brains. Hence, it is suggested that the normal neural pattern favours asymmetry with a larger and more powerful left hemisphere specialised for language. It is postulated that testosterone affects the rate of growth of the left hemisphere causing it to develop more slowly than the right. Slowed development of the left hemisphere might lead to structures in the right hemisphere becoming larger so that they can take over functions normally controlled by the left hemisphere. This might occur as the result of decreased cell death in the right hemisphere. Geschwind and Galaburda (1987) also suggested that the minor neurological abnormalities described above result from the effects of testosterone. These anomalies might be controlled by receptors for sex hormones which have been found in neural tissue in the new-born rat, and also in the cortex of the infant monkey.

A shift towards greater right hemisphere participation in left hemisphere functions would be stronger in most males than in females

since males are exposed to higher testosterone levels. This could explain the lower verbal but greater spatial abilities repeatedly found in men (Macoby and Jacklin, 1974; Wittig and Petersen, 1979).

This hypothesis is comprehensive in that it attempts to explain the higher number of left handers and males in the dyslexic population. However, evidence supporting the theory is circumstantial and indirect. Their basic argument is also circular. They set out to explain the higher incidence of left handedness in the dyslexic population and then use this finding to support their theory. Also, the studies linking dyslexia to left handedness all used self-identification as the test for the presence of dyslexia. Stronger support for the theory might come from a study of the handedness of a population of dyslexic children, where educational tests could be used to assess the presence and severity of the reading difficulty. This would provide an independent test of the theory.

1.5.8 - Subgrouping the Dyslexias

Many of the descriptions of the possible causes of dyslexia given so far have concentrated on the idea that there might be one unitary cause for this problem. However, the process of learning to read is complex and requires the association of several sensory inputs. Hence there might not be a single answer to the question: why do some children fail to learn to read adequately?

The first report which suggested that dyslexics might be classified into subtypes was published by Kinsbourne and Warrington (1963). They subdivided their population by comparing performance and verbal IQs of each child. One group consisted of subjects who had a performance IQ which was at least 20 points greater than their verbal IQ, while the second group showed a similar disparity but with the verbal IQ score

higher than the performance score. The group of patients who had low performance IQ scores also scored poorly on tests of finger differentiation and arithmetical ability. The group with the low verbal scores performed poorly on all tests of language ability. This dichotomy was compared to two cerebral disorders found in adults. The dyslexics who had difficulty with finger identification were in some ways similar to patients with Gerstmann syndrome (finger agnosia, left/right confusion, agraphia and acalculia). The dyslexics with verbal deficiencies were found to be similar to adult aphasics. The authors conclude that the results suggest that dyslexia should not be treated as a single entity but that the complex nature of the reading process should lead investigators to look for different cerebral dysfunctions which might account for the problems.

Since this time, several groups have attempted to distinguish dyslexic subtypes. The most popular sub-classification is into a visuospatial versus an audiophonological group (Boder, 1973; Mattis, 1978). All these investigators have suggested that the audiophonological subtype is much more common than the visuospatial subtype.

The subtyping described above can be compared with the different subtypes of acquired dyslexia. Hence, audiophonological developmental dyslexics may be likened to adults with acquired phonological dyslexia, and visual developmental dyslexics to acquired surface dyslexics.

Temple and Marshall (1983) described developmental phonological dyslexia in a 15 year old girl who could not decode either regular or irregular words if they were unfamiliar. Nonsense words were particularly difficult for this girl. This pattern was also found by Seymour and McGregor (1984) in an 18 year old girl.

Holmes (1978) described four dyslexic boys who showed a similar pattern of reading difficulties to that found in surface dyslexia. These boys showed phonic errors with regularisation of irregular words. This pattern was also described in several cases of developmental dyslexia by Seymour and McGregor (1984) although they avoided using the term surface dyslexia. These children had an impairment of sight vocabulary which was characterised by serial letter-by-letter processing.

Each investigator who has tried to subtype dyslexic children has used a slightly different battery of tests. Hence, although there is evidence to suggest that children with dyslexia suffer from either problems of an auditory nature, problems of a visuospatial nature or both, there is little agreement so far as to the exact nature of these problems or of their frequency. It has been suggested that the children with audiophonological problems might have left-hemispheric deficits while those with visuospatial dysfunction might have deficits of the right hemisphere (Duane, 1985).

1.5.9 - Eye Movements and Dyslexia

One possible explanation for visuospatial difficulties associated with dyslexia might be that some dyslexic children have problems with eye movement control. This would produce difficulties different to those found in dyseidetic dyslexics. These children are thought to have an impairment of sight vocabulary since they cannot recognise words by their overall shape. It is not likely that any deficit of eye movement control would be so severe as to prevent the child from distinguishing the overall shape of a word. What is more likely is that this might make it difficult for the child to scan the individual letters in words in the correct sequence. These children would pass

through the logographic phase of reading adequately, but might find difficulty in the alphabetic phase. In this phase of reading development the visual appearance of the letters has to be connected with individual letter sounds. This requires, not only that the child can differentiate the component sounds in the words, but also that they can sequence the letters in the word correctly. Snowling (1987) describes an experiment in which dyslexic children were compared with age matched controls on their ability to pronounce visually presented non-words. These words contained one- or two syllables, and within syllables there could be zero, one or two consonant clusters. The dyslexics were found to be poorer at this task than their reading age matched controls. Also, they made more errors on words with two syllables than on the one syllable word, and on words with consonant clusters. This experiment can be interpreted in two ways. The children were probably failing on this task as a result of poor knowledge of the rules of grapheme-phoneme correspondences. This might have been as a result of an inability to segment words correctly into their component sounds. Equally, the problem could have arisen as a result of an inability to correctly interpret the order of the letters in the word, especially in longer words with consonant clusters. Thus children with poor control of their eye movements might also be expected to fail in the alphabetic phase of reading development.

Many investigators have suggested that there is a difference in the control of eye movements between dyslexic and normal subjects (Zangwill & Blakemore, 1972; Rubino & Minden, 1973; Cuiffreda, Bahill, Kenyon & Stark, 1976; Rayner, 1978; Pavlidis, 1981a & b). The pattern of eye movement disorders which has emerged from these studies is that dyslexic children make more fixations and regressions, often fixate for longer and make less efficient saccadic eye movements. Zangwill

and Blakemore (1972) reported the case of a 23 year old male subject who could move his eyes accurately between two lights but who showed an increased number of reverse saccades, increased duration of fixation and who appeared to scan from left to right in some instances when attempting to read print. Pavlidis (1981a) studied a group of normal readers and compared these to a group of dyslexics. He found that the normal readers made regressive movements when reading print which were smaller in size than the preceding saccade whereas the dyslexic children made regressions of various sizes some of which were bigger than the preceding forward saccade. Pavlidis suggested that this pattern of eye movements might be diagnostic of reading difficulties.

However, regressions found when eye movements are measured while the subjects are reading text have two possible causes: the first is that the eye movement control is poor, resulting in unexpected backward movements of the eye. The second possible cause is that the subject has mis-read or misunderstood a piece of text and hence the eyes are purposefully regressed in order to re-read that text. This type of regression is likely to be found more often in dyslexic children who find reading difficult. It would not be a cause but a consequence of the dyslexia. Stanley, Smith and Howell (1983) and Adler-Grinberg and Stark (1978) investigated what was causing the increase in the number of regressions made by dyslexic children. The number of regressions made during a reading task was compared to that made while performing a visual search task. Although the dyslexics made more regressions than normal readers while reading, there was no difference in the number of regressions made during visual search. This would suggest that the number of regressions is the result of the reading difficulty rather the cause.

Pavlidis (1981b) reported a study which contradicted these findings. He measured the eye movements of dyslexic subjects while performing a sequential task with no relation to reading. In this study, subjects were required to track a series of single light sources illuminated sequentially. In this test, the dyslexics were again found to make more regressions than control subjects.

Stanley, Smith and Howell (1983) tried to replicate Pavlidis' results, but failed to find any difference between normal subjects and dyslexics using a task similar to Pavlidis' sequential tracking task. Pavlidis (1983) attributed their failure to differences in the spatial-temporal properties of the stimulus used. He claimed that the distance between lights was fixed at 4 degrees since this falls in the parafoveal region. The parafoveal region was chosen since eye movement control in this region was said to be accurate to 15-45%. The LEDs used by Stanley et al were placed only 1 degree apart - in the foveal region. This region may show more accurate eye movement control; hence the chances of finding any differences in eye movement control between normals and dyslexics would be reduced.

Another important difference between the two studies was the length of time for which the lights were illuminated. In the study reported by Stanley et al the lights were illuminated for either 500 or 1000 msecs. This was only half the duration used by Pavlidis (1-2 secs.). A random time interval between sequential illuminations was used by Pavlidis in order to prevent prediction of the time of onset of the next LED. This makes it more difficult for the subject to co-ordinate stimulus and eye movement. Pavlidis also states that some of the dyslexics made more adjusting movements when attempting to fixate steadily one light for 2 secs. This type of difficulty might not be found using shorter illumination times.

So far, therefore, the theory put forward by Pavlidis that dyslexic children have reading difficulties because of erratic control of saccadic eye movements has neither been replicated nor disproved. However, it seems just as unlikely that eye movement control would be the sole cause of dyslexia, as that all dyslexics suffer from problems of short-term memory or linguistic difficulties.

However the possibility that some children have reading difficulties as a result of abnormal eye movement control is worth further investigation. Other eye movement control systems might be implicated in addition to the saccadic system. Pavlidis' suggestion that dyslexic children find it harder to maintain steady fixation on a single LED for a relatively long period might be relevant. The array of lights was viewed at a distance of 50 cms. Hence the subjects would have to maintain a slightly converged position in order to fixate the light. It is possible therefore that their difficulty in maintaining fixation is connected to a dysfunction of the vergence control system. In this thesis, the possibility that some dyslexic children demonstrate a disorder in the fine control of vergence eye movements, and that it is this disorder which makes learning to read difficult, will be investigated.

1.6 - Vergence Eye Movement Control

In order to examine an object of interest at any point closer than optical infinity, it is necessary for the eyes to move in opposing directions (disconjugately) to bring the target on to the fovea of both eyes (binocular fixation). These eye movements are accompanied by a change in the shape of the lens which brings the plane of focus of the eyes to the point of interest (accommodation). Small changes in the size of the pupil are also seen. The combination of changes in

these three systems is called the 'near response'.

There are several cues which can be used by the brain to indicate that a disconjugate (vergence) change in eye position is required. The most important of these is the difference in the positions of the images of an object on the two retinae (retinal disparity), which is the main stimulus for vergence eye movements. Retinal blur is the major stimulus to the accommodation system. Investigation of the systems controlling changes in vergence and accommodation had to await the development of measurement techniques, which were sensitive to movements of both eyes, and to changes in accommodation. It is only recently that these techniques have become available, hence the systems controlling vergence and accommodation are not yet fully understood. In this section, I will summarise the available information on the control first of vergence, then of accommodation in human adults. I will then describe what is known about the way these two systems co-operate to produce co-ordinated changes in vergence and accommodation. This will be followed by a section describing what is known about the development of vergence control in humans.

1.6.1 - The Vergence Control System

Two components of vergence control have been recognised. Westheimer and Mitchell (1969) showed that the stimuli required to initiate vergence movements could have very large horizontal or vertical disparities, or separation in time before vergence failed to occur. They also tested the effect of presenting different stimuli to each eye and found that even if the stimuli could not be fused they could initiate vergence eye movements. The movements were transient since the stimuli could not be fused. It is known that the spatial and temporal resolution of the fusional vergence system (the system which

maintains vergence position for fusion once an object of interest has been brought to the fovea in each eye) is much more precise (Ogle, 1962).

Panum's fusional area is described as the retinal area over which mismatched retinal images in each eye are still perceived as belonging to the same object in visual space. Panum's area at the fovea is very small (10 minutes of arc) when measured under static conditions in adults (Toates, 1974). The difference between this and the much greater tolerance of the systems controlling initial vergence eye movements, and the maintenance of binocular fixation has led to the suggestion that vergence movements consist, first, of a disparity vergence component which reduces large non-fuseable disparities (physiological diplopia) to bring objects of potential interest towards the foveae, and then a fusional vergence component which maintains the images precisely on the foveae of the eyes. The boundary between these is indistinct.

Fusional vergence requires that there are small errors between the retinal positions of the object of interest in the two eyes. These retinal disparities are normally only a few seconds of arc (Rashbass and Westheimer, 1961). Any change in disparity is corrected by a negative feedback system which operates to minimise the error in retinal position in the two eyes.

The dynamic response of the vergence eye movement system is slow in comparison to other eye movement systems. Vergence eye movements take up to about 1 second to complete. The response latency is fast however - about 160 msec. Mathematical models describing the vergence control system have mainly been based on the idea of a leaky integrator (Rashbass and Westheimer, 1961) in which the output of the system is derived by integrating the input. This adequately explains the gain

response of the vergence system, but fails to explain the measured phase lags. The model overestimates the lag between an error and correction of that error. Two attempts have been made to resolve this difficulty. Zuber and Stark (1968) showed that there was a small difference in response time when predictable sinusoids were compared to pseudorandom sinusoidal stimuli. They suggested that the vergence system was able to predict the required change in vergence response from a knowledge of the stimulus waveform. Krishnan and Stark (1977) incorporated a velocity sensitive component into their model to explain the smaller phase lag. However, neither of these models have gained enough experimental support to be fully accepted. Hence there is no complete description of the vergence control system.

1.6.2 - The Accommodative Control System

The main cue for changes in the level of accommodation come from the retinal blur which occurs when the object of interest is not within the plane of focus. Campbell (1954) showed that the accommodation reflex is activated only when the level of illumination exceeds the threshold for foveal cones. Blurred images falling on the parafovea do not stimulate accommodation.

Retinal blur is an 'even-error' signal i.e. the effects of moving an object towards the subject are the same as those resulting from a movement away from the subject. Fincham (1951) showed that the first accommodation response resulting from a change in the position of depth of an object is nevertheless always made in the correct direction. Hence the brain must be correctly informed of whether the object has moved towards or away from the subject. Fincham (1951) suggested that the difference in the point of focus of red as opposed to blue light at the retina (chromatic aberration) or the different

shape of the blur circles around objects (spherical aberration) could be used to correctly sign changes in accommodation. The importance of these cues has more recently been confirmed (Kruger & Pola, 1986). Measurements of the initial direction of accommodation made in monochromatic light have shown that some subjects do fail to accommodate correctly when chromatic aberration at the retina is removed. Other subjects seemed to depend more on spherical aberration signals.

Two mathematical models have been proposed for the control of the accommodative system. Toates (1970, 1972) proposed a proportional control system in which the required output of the system is derived by multiplying the input error by a constant. Krishnan and Stark (1975) modelled the accommodative system using a leaky integrator similar to that suggested for the vergence control system. Both these models adequately explain the experimental steady state data from investigations of the accommodative system. However, attempts to use simple transfer models to explain the dynamic response of the accommodation system run into the same problems as those encountered when modelling the vergence system. The measured phase lag of the accommodative system is much smaller than that predicted by either model. The accommodative system reacts similarly to predictable and pseudo-random sinusoidal stimuli (Krishnan, Phillips and Stark, 1973) so that a predictive component cannot be incorporated to explain the differences. No other model has been proposed which adequately accounts for the measured gain and phase response of the accommodative system.

1.6.3 - Vergence-Accommodation and Accommodative-Vergence

When targets are viewed through pinholes in order to remove any

accommodative stimulus, changes in vergence position are still accompanied by changes in the level of accommodation (Fincham and Walton, 1957). This change in accommodation caused by changes in vergence is called vergence-accommodation. The gain of this change is found to be close to 1.0 in young subjects, but decreases with age and deterioration in the elasticity of the lens.

In a similar way, the vergence position of the eyes can be shown to change in response to a change in accommodation. This accommodative-vergence was first described by Muller (1826) (reported in Kenyon, Cuiffreda and Stark, 1978). The gain of the change in vergence attributable to accommodation was found to be 0.65 in a large clinical survey (Morgan, 1968) although it too was found to be larger in young subjects (Alpern and Larson, 1960).

1.6.4 - Interactions between Vergence and Accommodation

Three descriptions of the interactions between vergence and accommodation have been proposed. The first was a hierarchical interaction introduced by Maddox (1893) and described by Morgan (1980). In this, the accommodative system was thought to have the major influence on the control of binocular fusion. Fusional vergence was thought only to correct small vergence errors remaining after correction of the accommodative error signal. This description is unlikely to be correct since removal of the accommodative vergence signal does not lead to large vergence errors.

A second hierarchical model was proposed by Fincham and Walton (1957). In this the retinal disparity signal was thought to be the prime mover in correction of vergence errors. The blur-driven stimulus acted as supplementary to this error signal.

A third model dependent on linear interactions between vergence and

accommodation cues was proposed by Hung and Semmlow (1980). This gives an adequate description of the steady state interactions between vergence and accommodation. However, Cumming and Judge (1984) showed that the dynamic responses of both vergence and accommodation were determined predominantly by the vergence response. For both step and sinusoidal stimulation, the dynamic performance of accommodation and vergence is greatly enhanced by binocular viewing (Cumming & Judge, 1986), suggesting a significant role for the disparity signal (vergence demand) in control of both vergence and accommodation in the dynamic situation.

That the subject should give preferential attention to the disparity error in the dynamic situation seems appropriate since the tolerance of the accommodation system to errors is significantly larger than that of the vergence system. Fincham and Walton (1957) showed that, in the steady state, the accommodation system would allow an error of about 2D before a change in accommodation was stimulated. The dynamic tolerance of the accommodative system was demonstrated by showing that when a pure retinal disparity signal was used to change the vergence position while having no effect on the accommodative effort required to focus the target, accommodative movements still accompanied change in vergence position. The subjects did not report any blurring of the target, however (Fincham and Walton, 1957). In comparison, tolerance to retinal disparities, the error signals for the vergence system is much smaller - rarely exceeding 20 minutes of arc (Ogle, 1962).

The dynamic response of the vergence system is also superior to that of the accommodative system. The latency for vergence movements is 160 msec. But the latency of the accommodative response is of the

order of 360 msec. The feedback loop time constants have been measured for both systems. The time constant for the vergence system was found to be about 200 msec (Rashbass and Westheimer, 1961) while for the accommodative system it was 250 msec (Campbell and Westheimer, 1960). Hence, the interactions between accommodation and vergence seem to be dependent on minimising the error signalled by retinal disparity at least in the dynamic control of binocular fusion.

Kenyon, Cuiffreda and Stark (1980) described one situation in which the disparity signal was not preferred for refixating targets moved in the midline. In patients with strabismus, accommodative rather than disparity driven vergence was found to provide the largest component of this refixation. These subjects seemed not to respond to disparity cues. Patients with amblyopia without strabismus, however, were found to use disparity cues more than accommodative cues. These observations show that the orthoptic status of the subject should be checked before determining which system is operating predominantly in refixation of targets moved in the midline.

1.6.5 - Development of Vergence Control

At least four steps are required before an infant can learn to follow objects moving in depth. First it is necessary that the object of interest be brought onto the fovea of each eye (binocular fixation) and maintained there (static vergence control). Secondly, dynamic control of vergence movements has to develop to allow an object of interest to be tracked in depth. Thirdly, not only has an object of interest to be placed on the centre of each fovea, but the brain has to learn to perceive the image on each retina as belonging to the same object (binocular fusion). Finally, the accommodation system has to develop sufficiently to allow the infant to accommodate at the plane

of interest.

Ling (1942) concluded that binocular fixation does not appear until 7-8 weeks after birth in human infants. Aslin (1977) used corneal photography to confirm this result, and found that bifoveal fixation was not present until 2-3 months after birth. The tolerance of the static vergence system seems to be much larger at this age than it is in adults since Aslin and Dumais (1980) found that placing prisms of 2.5 or 5 degrees in front of the infants' eyes did not cause refixation movements. They suggested that this reflects a larger Panum's area in infants.

Fox, Aslin, Shea and Dumais (1980) showed that infants of 3.5 months were able to track a random dot stereogram moving in depth. Hence the vergence system is able to use pure retinal disparity signals to control movements in depth by this age.

The perception of random dot stereograms has also been used to assess the development of binocular fusion in infants. It is impossible to detect the disparate pattern in these stereograms unless the two halves of the stimulus are perceived as one object i.e. unless binocular fusion has already occurred. Atkinson and Braddick (1976) therefore used large disparity random dot stereograms to assess the development of stereopsis in infants. They showed that one in four 2 month old infants tested could reliably differentiate between targets containing vertical and horizontal disparities. This suggests that binocular fusion of targets can develop by two months of age. However, as mentioned above, Fox, Aslin, Shea and Dumais (1980), using moving random dot stereograms, found that stereopsis had not developed by 2.5 months though it was present by 3.5 months. The later onset of binocular fusion was thought to be caused either by the inability of young infants to fixate bifoveally, or by the incomplete neural

development of the binocular system. The discrepancy between the age of onset of binocular fusion found by these authors as compared to Braddick, Atkinson and French (1979) might be explained by the larger retinal disparities used in the latter study.

Birch, Gwiadza and Held (1983) also tested for the time of onset of binocular fusion using stereopsis as a measure. They pointed out that the ability to fuse binocularly might precede the ability to fixate bifoveally. If this were true, stereopsis might be detectable in younger infants if the stimuli were placed on the horopter, thus removing the need for fixation eye movements. However, when they tested this hypothesis they found that stereopsis was still not detectable until 4 months. This suggests that the binocular visual system has not fully developed until this age. Crossed disparities were found to develop 5 weeks earlier than uncrossed disparities.

Lewis, Maurer and Blackburn (1985) found that infants of 1 month old could detect a smaller width line stimulus in the temporal visual field than in the nasal visual field. This difference disappeared by 2 months of age. This data might help to explain why crossed disparities develop before uncrossed disparities, since it seems that the visual acuity of the region of the retina used to detect crossed disparities develops faster than the part of the retina used for uncrossed disparities.

Braddick, Atkinson and French (1979) showed that 1 month old infants can often accommodate out to 75 cms. By 6 months this range has usually doubled to 150 cms. Some younger infants could accommodate to 150 cms earlier than six months, showing that the mechanism may be developed by this age. Poor acuity, or limited attentional field might prevent the full accommodative range from being measured in all infants.

The studies presented above suggest that the gross development of binocular fixation is present by the third month, vergence eye movements and binocular fusion are present by the fourth month and gross accommodation is present by the sixth month after birth.

However, all these studies were carried out to determine the onset of development of the systems investigated. Few studies have investigated the progress of these systems to their adult levels. In one study carried out by Kowler and Martins (1982) the steady fixation measured at optical infinity of two pre-school children was compared to that of adults. It was found that the children were significantly worse than adults in this task. The children made larger saccades while attempting to maintain steady fixation than the adults.

In view of this data and of the attempts being made to link poor eye movement control to the process of learning to read, and to the specific difficulties some children have in this process, it would seem worthwhile to study the normal development of the eye movement control system.

In this thesis, I will present data suggesting that the development of the vergence control system in some children with learning difficulties is significantly inferior to that of their peers, whether the peer group is determined by a chronological or a reading age comparison.

Chapter 2 - Eye Movements during the Dunlop Test

Introduction

In the 1970's, Dunlop, Dunlop and co-workers (1972, 1973a & b, 1974, 1975, 1981) published several papers discussing the problems associated with defining the 'dominant eye' in children with reading disability. In these papers, they pointed out that assessment of the dominant eye was frequently based on measures of the eye used in monocular situations e.g. when sighting through a telescope. They noted that such studies were largely unsuccessful in proving links between eye dominance and reading difficulties (Belmont & Birch, 1965, Colman & Deutsch, 1964, Shankweiler, 1963, Zurif & Carson, 1970). Dunlop et al argued that assessment of the eye used to control binocular activities might prove more useful since reading is a binocular skill.

Other workers had also realised the need for a method of assessing the eye controlling binocular functions. Bettman, Stern, Whitsell and Gofman (1967) used tests based on the suppression of one or other visual image to try to assess binocular controlling eye. They found it impossible to nominate one or other eye as dominant in this test, even using normal subjects. A similar result was reported by Helveston, Billips and Weber (1970). Other workers who attempted to use retinal rivalry to assess the binocular controlling eye also failed (Raynard-Smith, 1970).

A survey of the literature on the nature of the cortical control of binocularity provides a possible explanation for the failure of these techniques. Binocular cells in the occipital cortex respond to simultaneous input from both eyes more strongly than when the image is seen by only one eye (Blakemore & Pettigrew, 1970). These cells are

tuned for the location of the image on the retina and the degree of disparity between corresponding points in the images arriving from each retina. If the images from each eye prove too dissimilar the output of the binocular neurones is suppressed. Hence, any attempt to assess which eye is controlling output from these cells requires that the inputs are not so dissimilar that they cause inhibition of the output. Obviously, therefore, tests based on suppression and retinal rivalry will prevent a truly binocular response from these cells.

Dunlop (1981) described a way in which the visual system may cause confusion when learning to read. He measured the eye movements of a dyslexic boy at 8 years old and again at 14 years old. He found a considerable difference in the types of errors at each age. At 14 years old, the boy showed the extended fixations and increased number of regressions reported previously for dyslexic children (e.g. Zangwill & Blakemore, 1972). However, at 8 years old the pattern was very different. The errors were of a disconjugate nature with both over-convergent and over-divergent movements of the eyes. The boy seemed unable to control his eyes together. These types of errors in eye movement control could lead to movement of letters and words both in relation to one another and in depth. The print might also appear to change size and become blurred as accommodation changes are linked to the changes in vergence position.

In summary, the Dunlops and their co-workers have suggested that some, though certainly not all, dyslexic children may be experiencing difficulties in learning to read as a result of difficulties in binocular control, brought about by the lack of development of a controlling eye for binocular functions.

In order to test this hypothesis, Patricia Dunlop developed a means of assessing the controlling or 'reference' eye in binocular

situations. Her criteria for this test were strict:-

a) The visual information had to be similar enough to allow full binocularity at all times, but have some difference (monocular 'controls') which would allow the test operator to ensure that the subject was maintaining binocularity.

b) The test had to involve some means of demonstrating the eye which controlled binocular function.

The test which was developed to assess binocularity was based on experiments on appreciation of fixation disparity during disconjugate movement of the eyes. Fixation disparity is the small difference in the retinal locations of the two fused images of an object which is being binocularly fixated. Ogle (1962) used this to test which eye was dominant when determining visual direction in binocular situations. This test requires a binocular target since both eyes must have equal chances of showing dominance. Ogle (1962) also describes a motor aspect of ocular dominance:

'This motor aspect most certainly is concerned with the maintenance of a stable visual space - a stability that persists in spite of eye movements. When attention is directed to a given point of fixation in binocular vision, it is the subjective egocentric spatial directions associated with the "local signs" of the retina of the dominant eye and their connexions in the cortex that provide the spatial orientation of the observer.'

The experimental apparatus used to measure ocular dominance of this sort incorporated a fused binocular stimulus, with an added monocular component for each eye. The eyes were moved disconjugately to provide a motor signal. In this situation, there is a strong illusion of movement of one or other of the monocularly viewed targets. The eye seeing the stationary target is taken to be providing motor and sensory visual stability, and is defined as the dominant eye or the eye used to calculate visual direction.

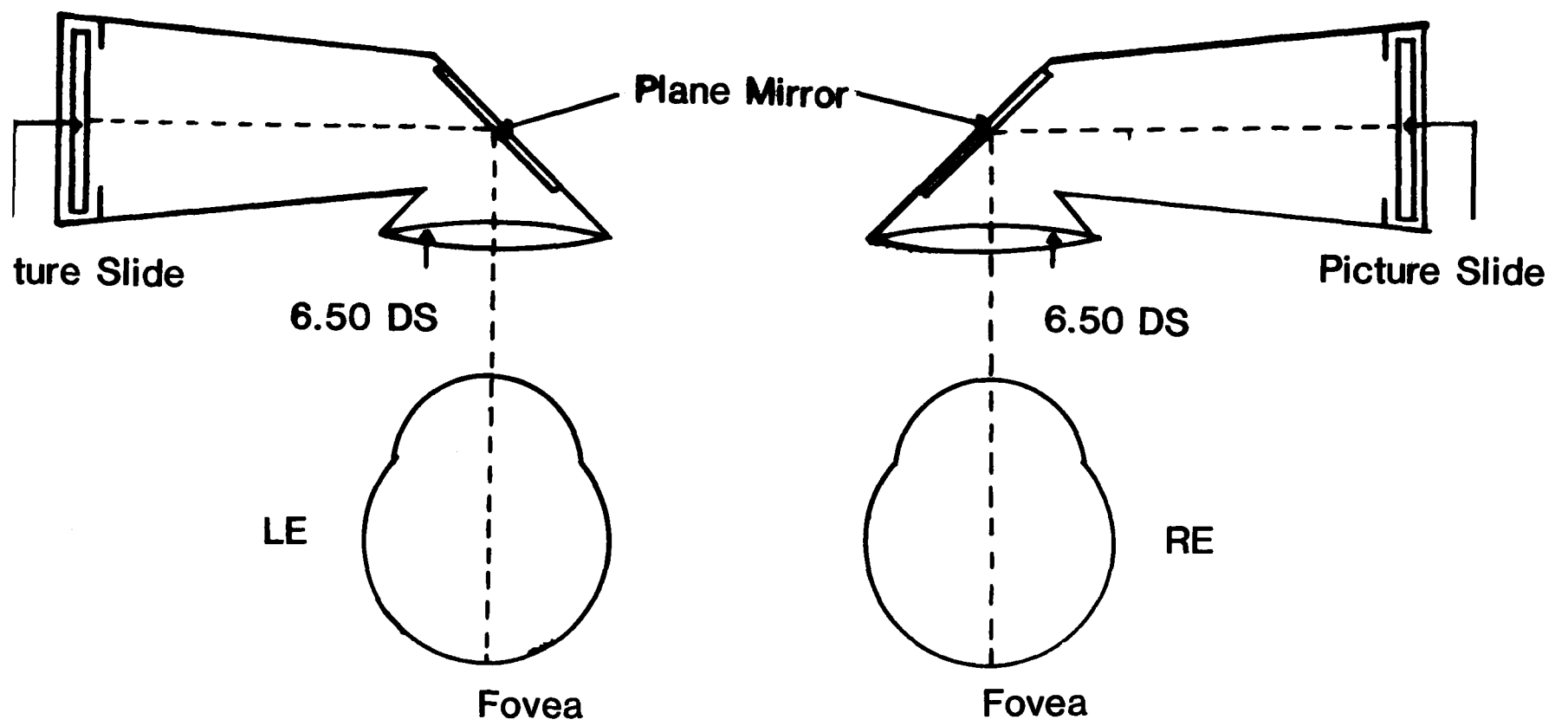


Figure 2.1 - A schematic drawing of the synoptophore.

This experiment was adapted by Dunlop et al (1973a). Small visual targets (3 degrees of arc) were projected separately to each eye using a synoptophore or major amblyoscope (Figure 2.1). Lenses in the synoptophore (6.5 DS) ensured that no accommodative effort was needed to see the targets clearly; thus the test was performed at optical infinity. The targets used by the Dunlops were Clement Clarke fusion slides F69 & F70 which depict a small house with a central front door (Figure 2.2). In the slide projected to one eye a small tree (monocular control) was seen to the left of the door while the other eye saw a large tree on the right of the door. The pictures were projected to the subject at the angle of fusion and a binocular image of one house with a tree on either side of a central front door was seen by most subjects.

In order to stimulate vergence, a retinal disparity was induced by slowly moving the targets disconjugately across the retinae. This produced a vergence movement of the subject's eyes as they attempted to track the targets in order to maintain fusion. Tracking movements of the eyes cannot be produced without some sort of error signal to precipitate the movement; the initial shift of the targets across the retinae provides a disparity signal which elicits an equal and opposite movement of the two eyes designed to retain the images of the house on the foveae. Perceptually, the images remained fused, and the house remains single so long as correct vergence movements are stimulated. These movements retain the targets on the retinae thus they never exceed the limits of Panum's fusional area (the area of the retina over which retinal disparities existing between the two eyes are ignored and the images from each eye are interpreted as representing the same object).

In the case of a divergent vergence demand, the images of the trees

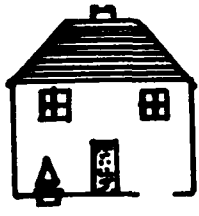


Figure 2.2 - Clement Clarke slides F69 and F70 used by Dunlop and co-workers during the Dunlop Test. The tree on each side of the door is used as a control to ensure binocularity throughout the test.

moved nasally over the retinae before vergence eye movements commenced. When the information from each eye is combined, each tree will appear to move towards the door seen by the other eye. This movement is then cancelled out by the opposite movement of the eyes which brings the images back to the nasal side of the fovea in each eye.

When this test is carried out in normal, fully binocular subjects, there is a consistent impression of movement of only one tree towards the door. The movement of each tree across the retina should be cancelled out immediately by an equal and opposite movement of the eyes to track the images. This is equivalent to the movement of an object in depth at the midline. The impression should therefore be that the house and the trees move either towards or away from the subject depending on whether the eyes are being converged or diverged. However, the apparent movement of one tree towards the door is on a lateral plane. Hence, only in one eye are the correct associations between the movement of the tree across the retina and the movement of the eyes being made. The relative position of the house and the trees will be dependent upon which eye's oculomotor signals are used to calculate visual direction. Since movement of a tree is seen consistently by one eye in most subjects, this would suggest that the oculomotor and retinal signals from the other eye are used preferentially in order to assess the relative lateral position of objects in space. The Dunlops called this eye the 'reference' eye.

This method of calculating visual direction becomes important when the eyes make vergence movements, since then the eyes are pointing in different directions with respect to the head. The two eyes should be directed to one point on the horopter. However, any object in front or behind the horopter in the line of sight of either eye will be imaged

at the same point on the retina. The lateral position of these objects will be misplaced unless their visual direction is calculated with respect to the vergence position of the two eyes. A simple means of making this calculation requires the relative lateral position of objects in space to be localised with respect to a stable reference point. The illusion of movement found in the Dunlop Test would suggest that in normal subjects this stable reference point is supplied by the visual direction of one or other eye.

The Dunlop test was found to give more consistent results when a divergent movement of the eyes was used (Dunlop, Dunlop & Fenelon, 1973a). This may have been a result of the higher accommodative element during convergence which may confuse the subject. Only the movement of a tree which appeared before fusion broke was used to assess the reference eye. If the tree seen by the left eye moved, the right eye was scored as reference, and similarly for movement of the tree seen by the right eye. Simultaneous movement of both trees was scored as no reference eye. The reference eye was also scored as negative in cases where the visual image from one eye was suppressed. However, in such cases, no visual confusion symptoms were expected since the viewing conditions were no longer binocular.

The Dunlops believed that the reference eye should be considered in relation to the dominant (or 'preferred') hand. They suggested that their test of the reference eye for binocular function could be used to determine whether the laterality of hand and eye was on the same or on opposite sides. Previous studies had suggested that the proportion of dyslexic children with dominance of eye and hand on opposite sides (crossed lateral) might be higher than in the normal population. Most of these studies, however, used measures which assessed only monocular eye dominance. These were largely unsuccessful in proving links

between crossed laterality and reading difficulties (Ogle, 1962, Porac and Coren, 1977).

In the study reported by Dunlop, Dunlop and Fenelon (1973a), the reference eye was compared to the preferred hand for writing. Subjects were scored as having 'crossed control' if the reference eye was on the opposite side to the preferred hand. In their study, they compared the abilities of 15 normal subjects with an age- and I.Q. - matched group of 15 reading disabled subjects in a selection of tests designed to assess binocular functions. These included standard orthoptic tests such as measuring the near point of convergence with the RAF rule, Maddox rod and wing tests of orthophoria, tests of coarse stereopsis, fusion, and fusional amplitude using the synoptophore, and tests of monocular and binocular eye dominance.

The authors looked for a combination of responses on binocular tests which would differentiate the reading disabled group from normal subjects. Three tests in combination proved successful in differentiating all but one subject. These were esophoria (latent convergent squint), coarse stereopsis and crossed control in the reference eye test. Convergence defects, defective stereopsis and crossed control were significantly different in the two groups, with the reading disabled group being more likely to be affected on all tests. Differences between the two groups in a test of crossed laterality using a monocular sighting test were not statistically significant.

Dunlop et al found these preliminary results encouraging since they implied that the Dunlop test, along with other tests of binocular function, might be used to predict cases of reading disability due to visual dysfunction.

In their study, the control group and the dyslexic group were

matched by age. Bryant and Bradley (1985) provided strong arguments showing that a control group matched to the dyslexic group by reading age allows a more stringent test of deficit hypotheses. They argued that any deficit found when comparing dyslexics to age matched controls may be attributed merely to the greater reading experience of the control group; hence the deficit would be a consequence of the reading difficulty rather than the cause of it. In order to be able to discount this possibility it is necessary to compare two groups who have had equal experience of text. This comparison was not made in the study reported by Dunlop et al, and so it is impossible to determine the causal relationship between their proposed deficit and reading disability.

The combination of tests used to differentiate between the normal readers and the dyslexics allows a different interpretation of their results. Two out of three of the tests are dependent on accurate vergence control. Children with large esophorias and poor stereopsis may be disabled in their ability to control their eyes together when disconjugate movements are required. This on its own might be sufficient to cause a reading difficulty since reading requires accurate vergence control in order to binocularly fixate small letters.

The Dunlop test was therefore used in a modified form by Stein and Fowler and co-workers (1981, 1982, 1984, 1985, 1987a&b) to assess binocular function in children with reading difficulties. They made two changes to the test used by Dunlop et al. Firstly, the picture used for the test was altered slightly (Figure 2.3). Instead of trees on either side of the central front door, a post with a circle on the top replaced one tree and a post with an arrow on top replaced the other. It was found that the movement of a line parallel to the

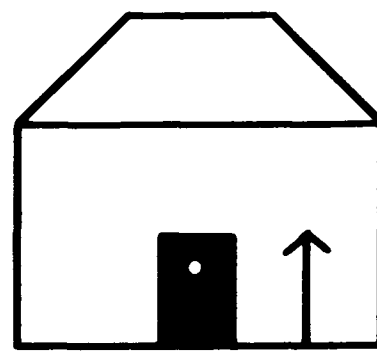
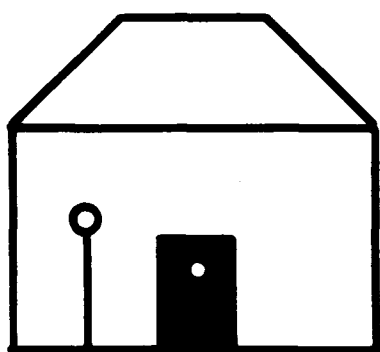


Figure 2.3 - Modified fusion slides used by Stein and Fowler (1985) in their version of the Dunlop Test. A parallel post is used for the control in this slide. The slide also has a white fixation point in the centre of the front door, to which children were instructed to attend. This slide was used for the Dunlop Test throughout the experiments described here.

upright of the door was more easily detected than movement of a line which was sloping. The central front door was also modified to be black with a white central spot. This central spot was used as a fixation point during the test in an attempt to prevent the subject from alternatively fixing the two posts. Second, they repeated the test a number of times. They found that many children did not respond consistently to repeated trials of the Dunlop test. Stein and Fowler therefore modified their testing procedure. Instead of testing each subject only once or twice, the divergent movement of the targets was repeated ten times in all subjects with frequent changes in the arrangement of the posts. The subject was asked to say which of the posts appeared to move on each occasion. A score of eight or more movements on the same side was scored as a stable reference eye. Three or more movements of both posts either simultaneously or successively was scored as unstable.

Unlike Dunlop, Dunlop and Fenelon (1973), Riddell, Stein and Fowler (1987) found no difference in the proportion of reading disabled children versus normal children who had crossed stable reference control measured using the Dunlop test of reference eye and the hand preferred for writing. The number of subjects used in their study (80) was very much larger than in the study reported by Dunlop et al. They did find, however, that significantly more children had failed to develop a stable reference eye when assessed using their modified Dunlop test. Dunlop et al would not have found this since they only measured the reference eye three times for each subject.

Stein and Fowler (1981,1985) explained the results of the Dunlop test in a slightly different way to Dunlop et al. Instead of stressing the importance of having the reference eye on the same side as the preferred hand, Stein and Fowler felt that the development of a

reference eye was the important factor. They felt that, in failing to measure the reference eye on more than one occasion, Dunlop et al had missed an important source of information on the nature of the difficulty some children were having with this test. In their studies, about two-thirds of the reading disabled population (average age - 9 years) were found to have unstable reference eyes.

In an attempt to force one or other eye to associate this information preferentially, Stein and Fowler gave children with unstable reference eye glasses with one lens occluded with an opaque material to wear for reading and writing. In a controlled study (Stein and Fowler, 1985), they reported that half of a group of children who started the study with unfixed reference developed stable reference while wearing the occluding glasses. On average, in a six month period, the children who developed a stable reference eye were found to increase their reading age by 5 months more than children who remained unstable. This suggested that these children were failing to learn to read, at least in part, due to their failure to develop a stable reference eye.

The results of this study on dyslexic children have been replicated, at least in part, by two other groups working in orthoptic departments (Starbuck & Whitelaw, 1986, Hodges, 1986).

Other workers however have failed to replicate these results. Bishop, Jancey and Steel (1979) found that children who had developed stable reference eye were significantly better readers than those who had not. But they suggested that this difference was explicable in terms of the higher I.Q. of the stable group. Nevertheless this result does not contradict Stein and Fowler's findings. Bishop et al used a measure of IQ which would itself have been depressed by poor reading. Thus it was not clear that low IQ caused the poor reading.

However, the Stein and Fowler study is insufficient to prove a causal link between stability of reference eye and reading disability. Again, the missing factor is a suitable control group. In fact, this study provides no information on the proportion of children in the normal population who have unstable reference eye. Before claiming that this is a cause of reading disability, it is necessary to show that only children who have reading difficulties are affected in this way. To do this it is necessary to provide both a control group matched for the age of the reading disabled group and a control group matched by reading age with the control group.

A study of the normal population showed a developmental trend in the proportion of children with stable reference eye (Stein, Riddell and Fowler, 1986). Only 50% of children had developed a stable reference eye at 5 years old. This proportion increased by about 8% every year so that at 11 years old (the oldest age group assessed) about 95% of children had a stable reference eye. This study provides some of the necessary data to help prove a causal link between instability of reference eye and reading disability. At 9 years (the average age of the reading disabled population in the Stein and Fowler study) the proportion of children with unstable reference in the normal population was found to be 20%. The equivalent proportion of the reading disabled population affected was 60%. Hence a much larger proportion of reading disabled children had unstable reference eyes. A comparison of reading ability for the stable versus unstable groups showed that those children who had developed a stable reference were on average 18 months ahead in their reading ability. Nevertheless a control group matched for reading age is still required before this correlation can be shown to be causal.

A reading age matched control group was used by Bigelow and

McKenzie (1985) when they tested reference eye in a reading disabled population. They found a significant difference in the proportion of children with stable reference eye - 5/14 reading disabled subjects had stable reference eye whereas 11/14 normal reading age matched controls were stable (Fisher Exact Test, $p < 0.05$). Hence there is now published data to suggest a causal link between the stable reference eye and reading ability.

There is a study which contradicts this data, however. Newman, Wadsworth, Archer and Hockly (1985) studied a large normal population and found no correlation between the proportion of children with stable reference eye when they were split into groups according to reading age (measured using the Neale reading test) compared to intellectual performance (measured using the WISC-R). As many good readers as poor readers had stable reference eye.

In the group of children studied by Newman et al., however, the percentage of children falling 18 months behind the spelling and reading ability expected from their performance IQ was far higher than the percentage performing 18 months ahead of their expected abilities (60% against 8%). If this criterion were to be used to define a dyslexic population, the prevalence of dyslexia would be exceptionally high, and would include more than half the children in this sample. This throws doubt on the measures used to evaluate the IQ and reading abilities of the children. It is difficult, therefore, to compare these results with the results obtained by Stein and Fowler (1981) which showed that significantly fewer good readers had unstable reference eye than poor readers.

Thus, the modified Dunlop test may still hold out hope of being able to predict a group of reading disabled children who are having difficulty learning to read due to problems of a visual nature. Stein

and Fowler explain their findings by suggesting that some children fail to make reliable associations between the retinal signals from one eye and the oculomotor signals from that same eye. This difficulty in associating different types of information could lead to difficulties in judging visual direction accurately. When the eyes are converged, they point in slightly different directions. In order to correctly interpret the position of objects in space it is necessary to calculate visual direction from a stable reference point. If oculomotor information about visual direction is associated first with the retinal image from one eye and then from the other, the letters on a page could appear to shift in position. This would interfere with the process of associating the visual appearance and sequence of letters within a word with the phonemes constituting that word. Children with this sort of problem might therefore be expected to have difficulties in the alphabetic phase of reading development (Frith, 1985).

Both the Dunlops and Stein and Fowler emphasise the difficulties with this test. It demands concentration from both examiner and subject while the test is taking place. The subject has to interpret what he sees. He must not 'guess' or try to say what he thinks the examiner wants to hear. The examiner must not give subconscious clues to the answer required. The test will only work if the subject watches the central fixation spot and is aware of movement in the periphery. This is a difficult task for a young child and so requires a great deal of experience on the part of the operator in explaining what is required.

The only information about what happens during the Dunlop test comes from the answers given by the subject. This is information of a subjective, sensory nature. No information about what happens to the

oculomotor system during the Dunlop test is available. Information of this nature could be obtained by recording the eye movements of subjects while they perform the Dunlop test. In this chapter I discuss the results of experiments performed to measure eye movements during the Dunlop test in order to determine the relation of eye movements to the development of a stable reference eye.

2.2 - General Methods

2.2.1 - Subjects

Three groups of subjects were used for these experiments: 1) a clinical population of children with various degrees of learning difficulties, 2) a group of children who were known to have reading ability at least 2 standard deviations behind that expected for their I.Q., and 3) a group of normal children from local primary schools. Subgroups of these populations were tested in some instances. The maximum number of children in each group is given below. The number of children tested during any experimental procedure is also given.

1) This clinical population was formed by children aged 6 to 16 ($n = 352$) who were referred to the orthoptic department of the Royal Berkshire Hospital in Reading. These children were referred by their own G.P.s, school medical officers, educational psychologists or other medical referring agents. The reason for the referrals was that there was some concern, from the school, or parents, that the child was having unusual difficulty in learning to read. It was found to be impossible to perform I.Q. and reading age testing on all the children referred, so the severity of the reading problem is unknown for many of these children.

2) During a period from February 1985 to February 1987 a group of children referred to the Royal Berkshire Hospital for reading

difficulties and aged between 7,6 and 12,0 (n = 74) were assessed by Dr. Doris Kelly, a reading specialist. All the children were given four subtests of the British ability scales. Two of these subtests (Similarities and Matrices) are known to be relatively unaffected by the language difficulties found in reading disabled children (Thomson, 1982). Children who were found to have a reading age at least 2 standard deviations behind that expected from these I.Q. subtests were classified as 'dyslexics' and included in this study group.

3) Children aged 7,0 to 12,0 (n = 80) were seen in local primary and junior schools. These children underwent the same I.Q. tests as the study group (2) described above. This group formed a control population which included not only children whose reading was at or beyond their expected ability, but also, as expected, a proportion of 'normal' children who were actually reading disabled. All the groups contained a cross section of the population with regard to social class. The children all spoke English as their first language.

2.2.2 - Orthoptic Investigation

All children underwent a full orthoptic investigation. This included the cover test, ocular movements, testing the near point of convergence using the RAF rule, tests of binocular and monocular accommodation, visual acuity testing at both near and distance, and the Randot test of stereoacuity. This thorough examination allowed children with any visual anomaly to be excluded from the results reported here.

i) Cover test - This is used by orthoptists to test for latent or manifest deviations of the visual axes. The child is encouraged to fix a small accommodative target at 30 cms and 6 m. The orthoptist covers first one eye and then the other. If the uncovered eye is seen to

move, this indicates a manifest deviation. Children with this condition were excluded from the study. If no movement of the uncovered eye is detected, movement of the eye under cover as the cover is removed, is assessed. In exophoria, one or both eyes turn inwards as the cover is removed. An eye which turns outwards as the cover is removed is said to be esophoric. In eso- or exophoria, the tendency of the eye to turn is controlled by the fusional reflex: this maintains bifoveal fixation.

ii) Ocular movements - These were tested by asking the subject to look in the nine primary positions of gaze. This allowed the orthoptist to assess the action of all the eye muscles, in order to confirm that there was no muscle abnormality which might prevent the eyes from moving easily in any given direction.

iii) Near Point of Convergence - The conventional way to test for the near point of convergence is the RAF rule. A 60 cm rule was placed at eye level, and a target was moved towards the subject. When testing for convergence, the target was a small spot with no accommodative cues. The subject was asked to watch the spot as it approached, and to tell the examiner when the spot split into two. The distance of the spot from the subject was measured, and noted as the near point of convergence. Children under 12 years of age are expected to be able to maintain single vision in this test down to 6-8cm.

iv) Accommodation - The RAF rule was also used for testing monocular and binocular accommodation. In this test, the target consisted of small letters or numbers (N5 print). Again, the target was brought towards the eyes, but this time the subject had to report when the letters became blurred. This test was performed with both eyes open, and then for each eye separately. Note was made of the near point of accommodation: again this is usually 6-8 cms.

v) Visual acuity - This was tested using a Snellen chart. Since some of the children tested had difficulty naming letter shapes, the children were allowed to respond by giving the letter names, sounds or by drawing the letters with their fingers in the air.

vi) Stereoacuity - The Randot test was used to give an indication of the level of stereoacuity obtained by the children. This test is neither wholly 'global' nor wholly 'local' (Julesz, 1971). The stereoscopic image is an outline of a hoop with a random dot pattern background. This test was chosen because it is finely graded down to a difficulty of 20 secs of arc. Other commercial stereoacuity tests are either too crude (e.g. the Wirt test of stereoacuity is only graded down to 40 secs. of arc), or the steps between tests are too great to grade the stereoacuity finely (e.g. TNO which has jumps of 60, 30 and 15 secs of arc).

The test consists of ten sets of three hoops. These are viewed through a pair of spectacles with lenses which are polarised in opposite directions. These ensure that each eye sees a slightly different picture. In one of the three hoops, the images seen by left and right eyes are arranged to be slightly disparate. This gives an illusion of depth - the hoop seems to stick out from the page. The disparity between the polarised images decreases with each set of hoops (range - 400 secs of arc to 20 secs of arc). The child was asked to point to the hoop which stuck out. The test continued with each set of hoops until the child said that they had all become flat or until he made two mistakes. The stereoacuity was scored as the disparity at which the child last made a correct response.

Any child who was found to have abnormal ocular movements was omitted. Children with visual acuity below 6/6 in either eye were also excluded from the study.

2.2.3 - Dunlop Test

After the full orthoptic assessment, the children were given the Dunlop Test. This involved using a Clement Clarke synoptophore, which was set up so that the centres of the tubes matched the child's interpupillary distance (IPD). The angle between the tubes was set so that it was aligned with the angle of fusion for a particular child. In most instances this meant that the tubes started parallel, with the eyes pointing straight ahead. The slides used for the modified Dunlop test are shown in figure 2.3. Each slide consists of the outline of a small house with a central front door (2.5 x 2.5 degrees - 'macular sized'). The black, front door has a small white spot in the middle. This was used as a fixation point during the test. The slides contained different controls in that one had a post with an arrow to the right of the door, while the other had a post with a circle on the left of the door. These posts acted as controls so that the orthoptist could be sure that there was no suppression of one or other visual image. The slides were arranged in the synoptophore so that the posts projected onto the nasal field of each eye. When viewing the slides, the child saw a fused image of one house with a central front door, and posts on either side of the door.

Before the orthoptist began the Dunlop Test, the nature of the test was explained to the child. S/he was told to watch the spot in the centre of the front door, and to watch for the movement of one of the posts towards the door. Care was taken to ensure that the child realised that movement of the post could only be seen if the eyes remained fixated on the central fixation spot. This helped to ensure that the child did not either watch only one post during the test, or alternately fix each post.

After the explanation, the orthoptist started to move the tubes slowly (0.6 degrees/second) in a manner which usually resulted in a divergent movement of the child's eyes. The child was watched throughout the duration of the test to ensure that his attention did not wander. If the child looked away, the test was stopped, and started again. After 3-4 degrees of movement of the tubes, the orthoptist asked the child which post s/he saw moving. If the child was unsure, the test was repeated to give him another chance to perceive the movement. If the child could tell which post moved, s/he was told that the test would be repeated several times to see if the same post moved, or whether a different post moved. This procedure was repeated 10 times, with frequent changes in which eye saw which post to prevent guessing. The score was noted as the number of times out of ten the post seen by one eye moved. If the same post moved on 8 out of 10 testings, the child was said to have a 'stable' reference eye. The reference eye was defined as the eye on the side which viewed the stationary post most often. If both posts moved 3 or more times - either successively or simultaneously - the child was said to have 'unstable' reference.

2.2.4 - Amplitude of Fusion

The amplitude of fusion is a measure of the amount of vergence movement that the eyes can make under the conditions of testing presented by viewing in a synoptophore. This was measured under several conditions: different sized targets were used and the rate of change of the angle between the synoptophore tubes was also varied (see below). The angle of fusion was measured as the change in vergence angle between the start of testing and the point at which diplopia was reported by the child. This angle was measured on the

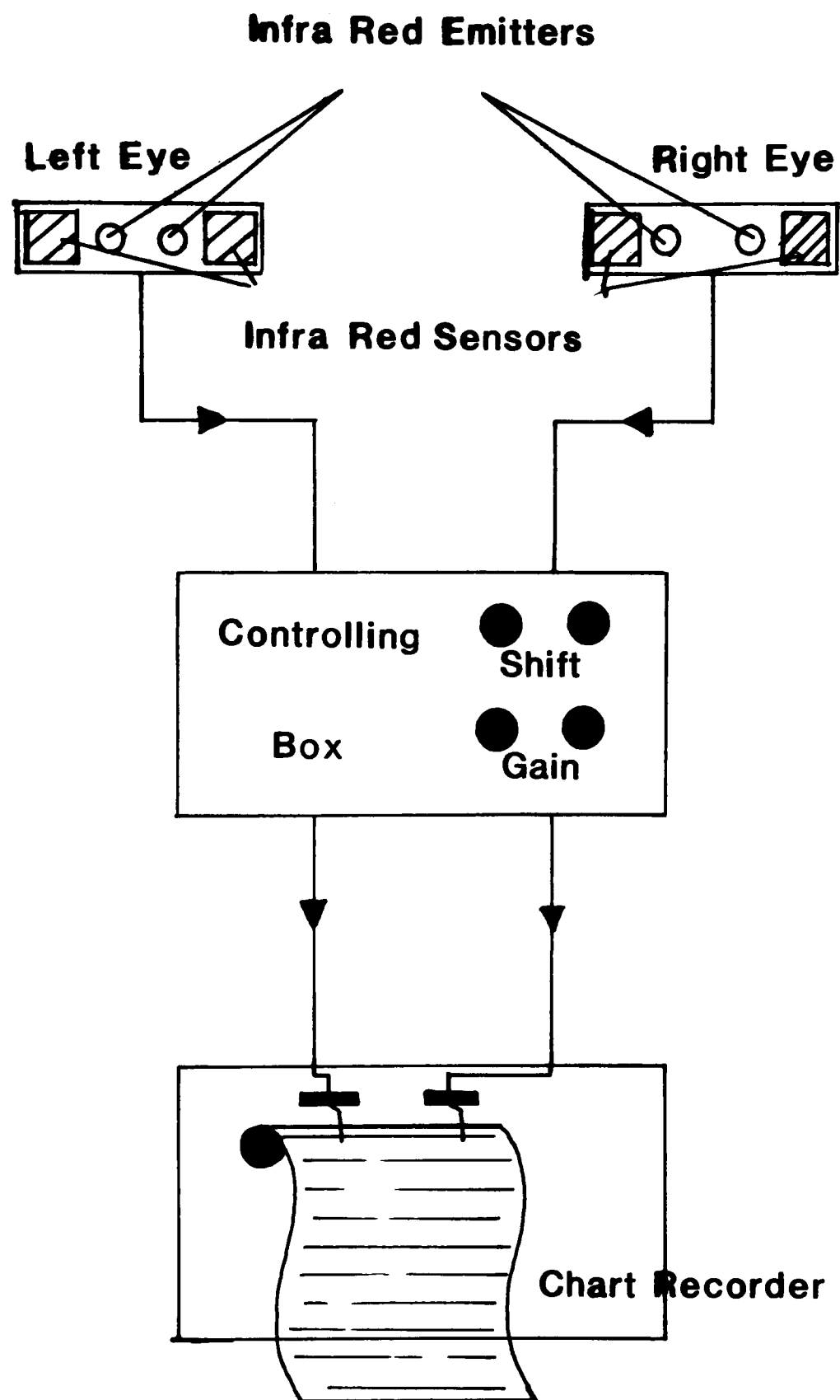


Figure 2.4 - A schematic diagram of the infra-red reflectometry apparatus.

synoptophore at the time of testing by the orthoptist, and was subsequently checked by measurements taken from eye movement recordings (see below). If vergence movements of the synoptophore tubes had stimulated only version movements of the subjects eyes, or if the vergence response to the movement of the synoptophore tubes was totally inappropriate, the eye movement was scored as showing 0 degrees of vergence. This measurement provided a quantitative measure of vergence performance.

2.2.5 - Eye Movement Recording

After the Dunlop Test, the child was asked to wear a pair of spectacles on which had been mounted an infra red reflectometry system (figure 2.4). In this system, two infra red sources are mounted 5mms apart on a perspex block so that they point at either side of the high contrast limbus of the eye. The infra red light is reflected differentially from the white, and the iris of the eye - more light being reflected from the white of the eye. As the eye moves from one side to the other, one or other of two photo detectors receive less infra red light proportionally to the area of pupil covering the source, and so a smaller voltage is received from this receptor. The signals from the two receptors are electronically subtracted to produce a differential signal. With careful alignment, this set-up has a linear range of about 15 degrees to either side of centre, and a resolution of about 1/10 degree can be achieved. The infra red light is chopped at a frequency of 10 KHz to make the signal less susceptible to contamination by changing light levels in the environment (Wheless, Boynton & Cohen, 1966).

The eye movement recorders were calibrated for each eye using a specially designed synoptophore slide. This was the same in each eye,

and showed a central fixation spot, and fixation spots lying 5 degrees to either side. The child was asked to fixate, first the central spot, and then each of the lateral spots in turn until the pen movement recorded for each eye was similar. The position of the perspex blocks could be altered at this time to ensure linearity of the signal.

The infra red reflectometry apparatus was used to record eye movements while the child performed the Dunlop test (divergent movements). Afterwards, the child's eye movements were also recorded while the child converged using the Dunlop test slides as stimuli. The recordings made during this test were assessed to determine whether the child had stable vergence eye movement control. Two measures were made in order to decide whether the eye movements were 'stable' or 'unstable', namely: the amplitude of fusion and the appropriateness of eye movements to the stimulus. Strict rules were applied to this qualitative categorisation. The eye movements were defined as unstable if:-

- a) Version instead of appropriate vergence movements were produced in response to vergence stimuli,
- b) The eye movements recorded were inappropriate for the stimulus in other ways (i.e. erratic eye movements). or c) Fusion broke after only 1/2 degree in divergence or 1 degrees in convergence.

The eye movements were categorised as stable if:-a) Appropriate vergence movements were made to both convergent and divergent stimuli and b) The fusion range measured more than 2 degrees in divergence or 4 degrees in convergence.

These criteria left the possibility of children who could not be assigned to either the stable or the unstable group. These were categorised as having unreliable eye movements.



Figure 2.5 - Clement Clarke slides F 147 and F 148. The Red Indian measured 1.5 x 2 degrees. The tomahawk and bow formed the controls for binocularity on this slide.

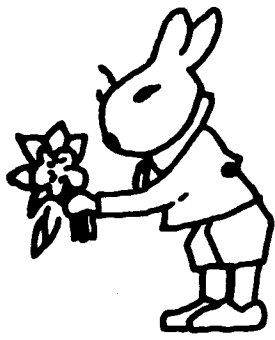


Figure 2.6 - Clement Clarke slides F 119 and F 120. A larger version of this slide was also used (Clement Clarke F 65 and F 66). The small rabbits measured 2.5×2.5 degrees of visual arc. The large rabbits measured 7×7 degrees of visual arc. The rabbit's tail and bunch of flowers acted as controls for binocularity.

2.2.6 - Target Size

Three fusion slides were used to assess the effect of changing the size of target on the maintenance of stable vergence control. The first of these was a foveal sized target (1.5 x 2 degrees). This target is shown in figure 2.5. It depicts a Red Indian with a bow and a tomahawk (Clement Clarke fusion slides F 147 & F 148) . In one of the two slides, the Indian only holds the bow while in the other he holds the axe. The axe and bow therefore act as monocular controls to allow the orthoptist to determine whether suppression occurs.

The macular sized target was 2.5 x 2.5 degrees (Clement Clarke slides F 119 & F120, see figure 2.6). This target depicts a rabbit. On one slide the rabbit holds a bunch of flowers but has no tail. The other slide shows a rabbit with a tail but no bunch of flowers. The flowers and the tail, therefore, act as controls.

The paramacular target was 7 x 7 degrees (Clement Clarke slides F65 & F66). This is the same picture of a larger rabbit with peripheral controls as shown in figure 2.6.

Since the foveal slide above showed a different picture from the macular and paramacular target, a complete set of targets were devised to ensure that the change in picture had not affected the results. Each of the different sized targets showed the same pattern (Figure 2.7). Targets of 7, 3 and 1 degree sizes were used.

2.2.7 - Speed of Vergence Movement

The effect of changing the speed at which the vergence movement was produced was also investigated in some children. The synoptophore used for these experiments was adapted to allow the movement of the tubes to be driven by motors. By varying the power supplied, the speed at



Figure 2.7 - Fusion slides designed to test the effect of changing the size of the stimulus on the amplitude of fusion during convergence. Slides of 7 degrees, 3 degrees and 1 degree were used.

was from 0.3 degrees/second to 1.4 degrees/second. The small foveal target (Red Indian) was always used for these measurements.

During all testing on the synoptophore, the children were instructed to watch a central fixation point on each of the targets. They were told that the target would break into two; and that they should indicate when this happened. The moment at which fusion broke was used as the end point of each trial. When vergence of the synoptophore tubes produced only version movements on the eye movement recording trace, the test was repeated with the child being asked to say if either of the controls disappeared. This allowed the examiner to identify cases in which the image from one or other eye was being suppressed. The children were not routinely asked to say if one or other post disappeared since it was considered that this would make the test needlessly complicated.

2.3 - Results

2.3.1 - Concordance of Dunlop Test and Vergence Eye Movements

In a study of 30 children reported by Stein, Riddell and Fowler (1987a), preliminary evidence was presented which suggested that the results of the Dunlop test correlated well with measures derived from vergence eye movement recordings of stability of vergence control. Reading disabled children with unstable Dunlop test results were shown to make more version movements and smaller vergence movements than either a reading disabled group with stable Dunlop test responses or a group of normal children. In the 1987 study, only an age-matched control group was used. The study was also limited to 30 children. The results presented here extend the comparison between the Dunlop test and vergence eye movement measurements to a larger sample. The same

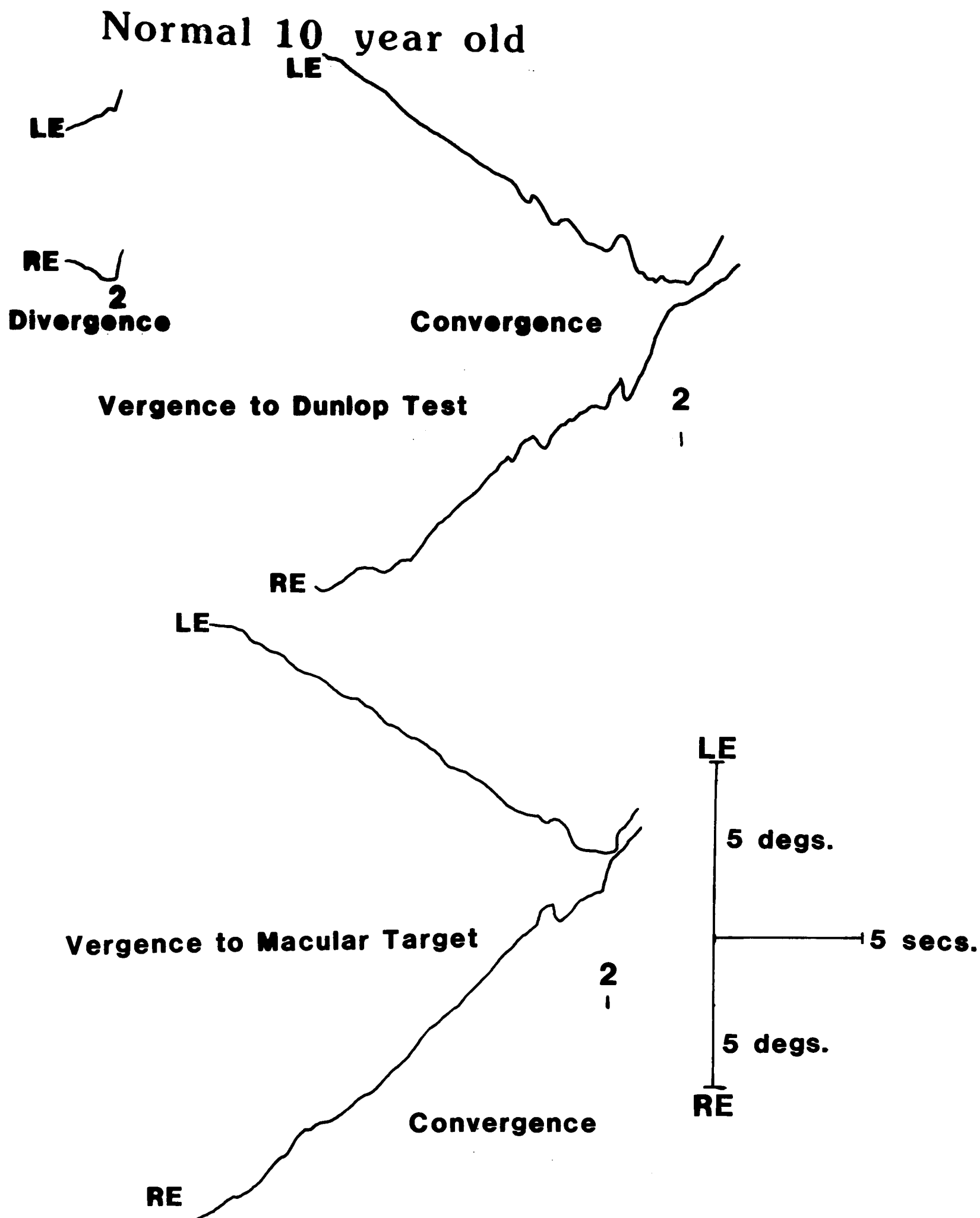
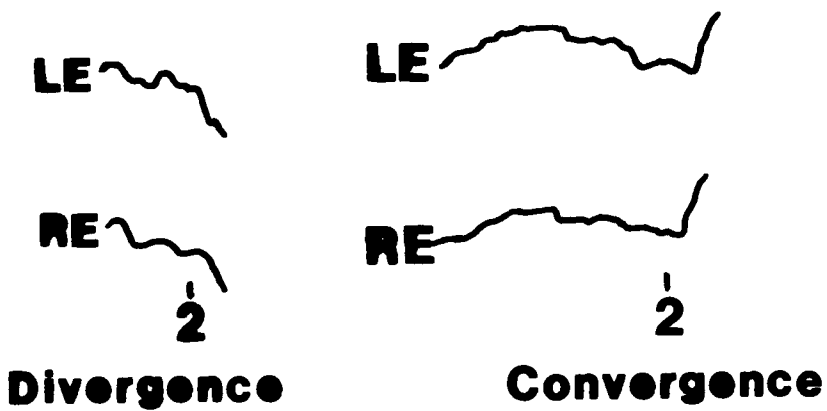


Figure 2.8a - Vergence eye movements recorded using infra-red reflectometry during convergence and divergence of the synoptophore tubes. The subject was a 10 year old male normal reader. The fusional stimuli used were the modified Dunlop Test slides and the small rabbits. Key: LE - left eye; RE - right eye; 2 - point at which child reported that fusion had broken.

Reading disabled 10 year old.



Vergence to Dunlop Test

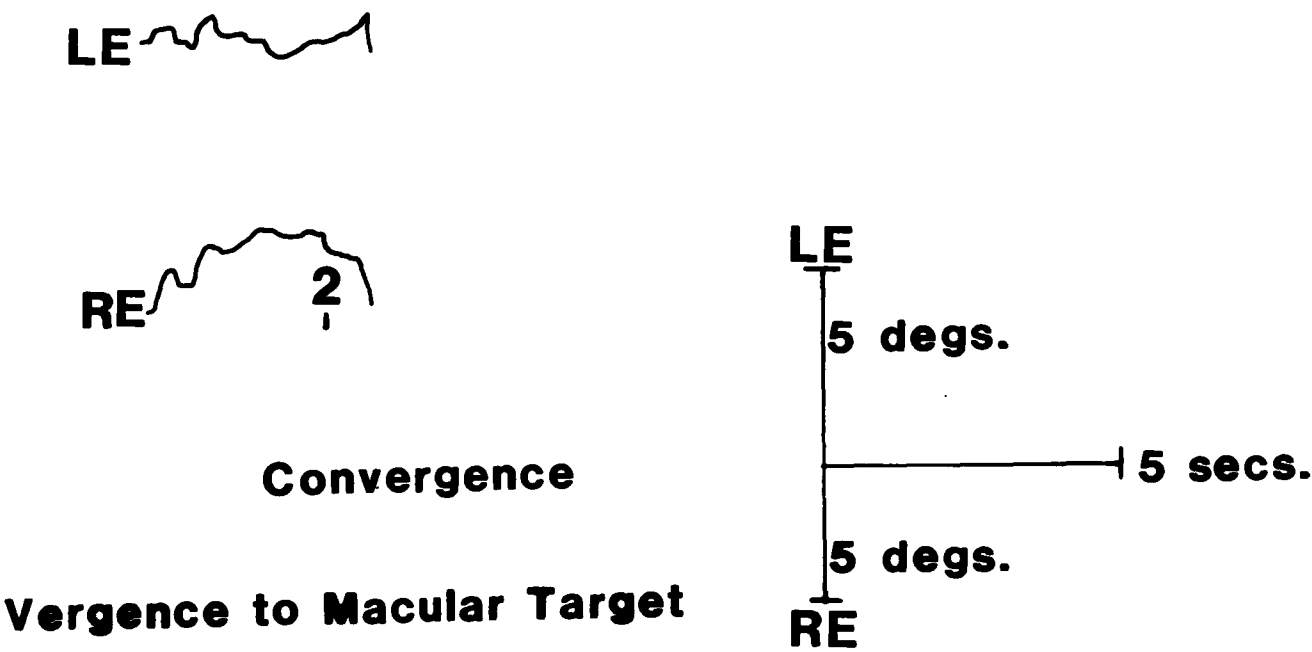


Figure 2.8b - Vergence eye movements recorded as above in a 10 year old dyslexic boy.

categorisation of eye movement recordings as stable or unstable was used as in the preliminary reports.

Figure 2.8a shows an example of the eye movements of a 10 year old child categorised as having stable vergence control. This shows the eye movements recorded during divergence and convergence using the Dunlop test slides. The traces start at the beginning of movement of the synoptophore tubes. The '2' near the end of the trace marks the time at which the child reported diplopia. The eye movements recorded in both divergence and convergence show clear vergence adjustments. The eyes responded symmetrically, and the vergence movements produced measure more than 2 degrees of divergence and 4 degrees of convergence. This recording meets all the criteria necessary to classify it as an example of 'stable vergence eye movement control'.

The eye movements recorded with a larger macular target are also shown. Again a clear convergent movement was produced in response to convergence of the targets.

Figure 2.8b shows eye movements recorded with the same stimuli for a 10 year old child categorised as unstable in the eye movement test. This time there was no vergence response to either divergence or convergence. Instead the eyes moved conjugately. As a result, the child reported diplopia very quickly. Since the eye movements recorded during vergence movements of the Dunlop test slides produced versional movements of the eyes, this recording fits the unstable categorisation.

The eye movements recorded in response to a larger macular stimulus show some evidence of appropriate vergence movements. Nevertheless, diplopia was still reported very quickly (after approximately 3 degrees of convergence). Hence a greater degree of vergence control was found for larger stimuli.

Using the criteria set out in the methods section and illustrated above, the results of the Dunlop test and vergence eye movement control were compared in 352 children from a clinical population (population 1. above). These children were all referred to the Royal Berkshire Hospital because they were showing some evidence of reading disability. There was no data about the severity of the reading deficit in this group. However the main object of the study was to compare the results of the Dunlop test with an objective assessment of the children's oculomotor control in a sample with stable and unstable Dunlop test responses. The assessment of the eye movements was performed before the results of the Dunlop test were known.

Of the 352 children investigated, 218 were found to have stable responses in the Dunlop test (62%) (Figure 2.9). The results of categorisation by eye movements showed that 204 children (58%) had stable vergence eye movements. Counting only the children whose results on the Dunlop Test matched the assessment of eye movement stability, 73.2% of the sample showed correspondence. Thus there was a high concordance between the results of the Dunlop test and a eye movement recording in a large population of unselected children.

The correspondence between Dunlop test results and eye movement stability was also investigated in a population of children whose reading age was more than two standard errors behind that expected from their IQ scores (Figure 2.10). In this (group 2) sample of 58 children only 44% had stable Dunlop test responses. The percentage with stable eye movements was even lower (30%). Correspondence between results of the Dunlop test and eye movement control assessment for both stable and unstable groups was found to be 72.4% in this sample. These results demonstrate the high percentage of children in the dyslexic population with unstable vergence eye movement control. No

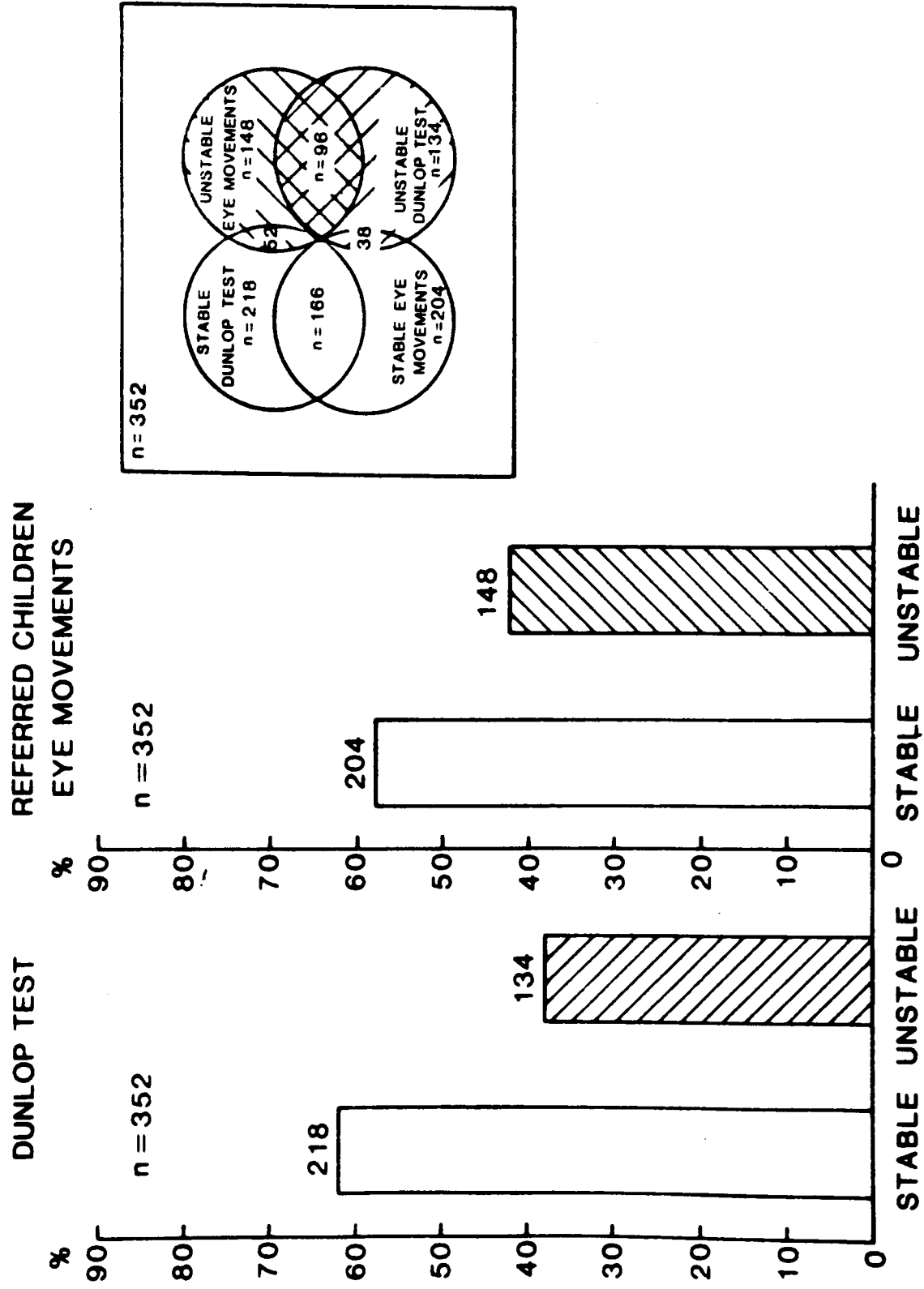


Figure 2.9 - Concordance between the results of the Dunlop Test and categorisation of eye movement recordings in a clinical population. The bar graphs on the left show the percentage of children classified as stable or unstable according to the Dunlop Test and vergence eye movement recordings. The Venn diagram on the right shows the distribution of the children into the four categories -

- i) Stable Dunlop Test responses and stable eye movements (n = 166).
- ii) Stable Dunlop Test responses and unstable eye movements (n = 52).
- iii) Unstable Dunlop Test responses and stable eye movements (n = 38).
- iv) Unstable Dunlop Test responses and unstable eye movements (n = 96).

DYSLEXIC CHILDREN

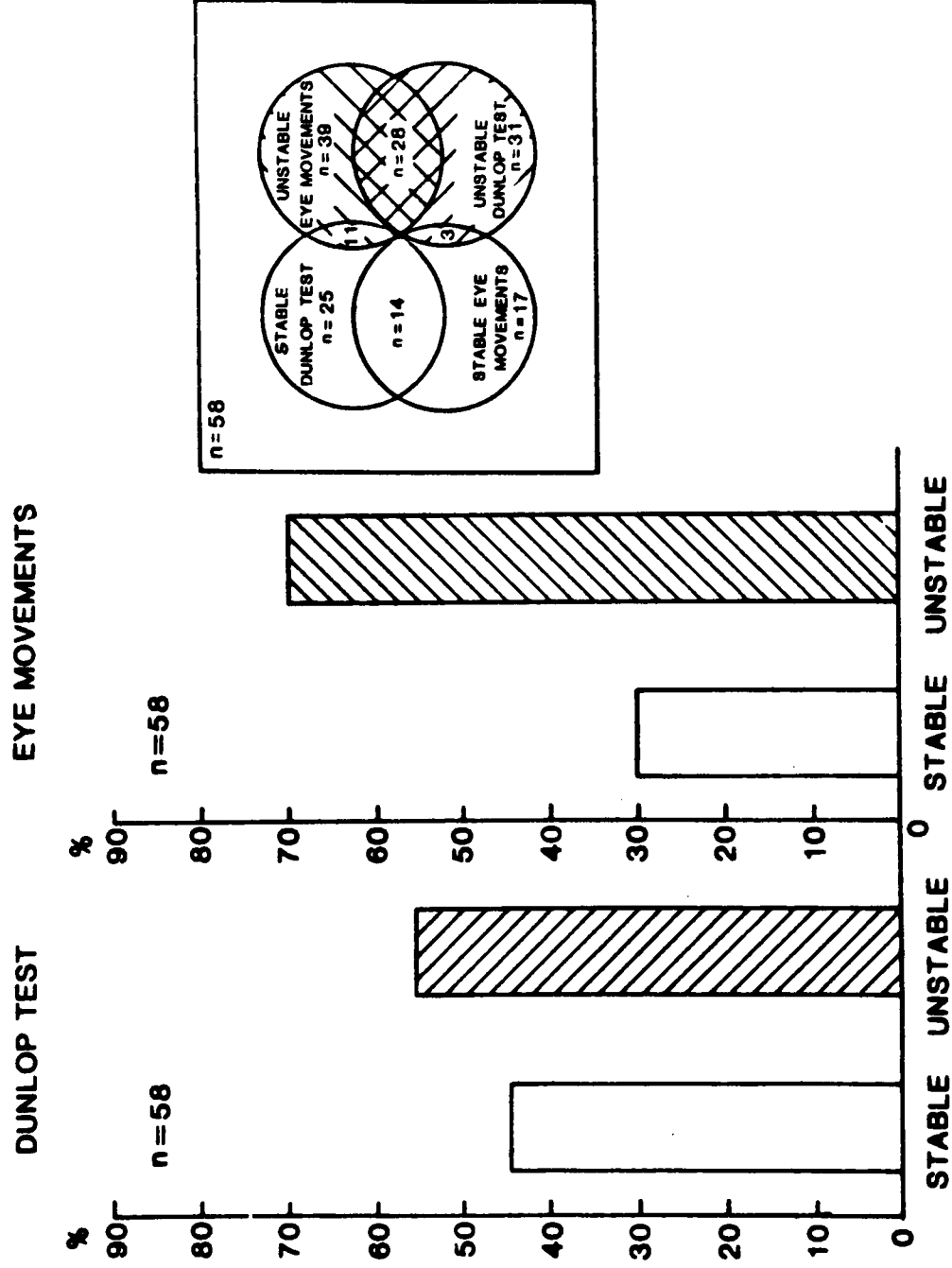


Figure 2.10 - Concordance between the results of the Dunlop Test and categorisation of eye movement recordings in a dyslexic population. The bar graphs on the left show the percentage of children classified as stable or unstable according to the Dunlop Test and vergence eye movement recordings. The Venn diagram on the right shows the distribution of the children into the four categories -

- i) Stable Dunlop Test responses and stable eye movements (n = 14).
- ii) Stable Dunlop Test responses and unstable eye movements (n = 11).
- iii) Unstable Dunlop Test responses and stable eye movements (n = 3).
- iv) Unstable Dunlop Test responses and unstable eye movements (n = 28).

conclusions can be drawn as to causality from this, however, until the proportion of normal readers, with unstable eye movement control matched for reading age is known.

The third group of children to be assessed were 58 children from a local primary school. This sample contained mostly normal readers. However, since it was representative of the normal population, some children with poor reading ability with respect to their IQ were also found. The percentage of children with stable Dunlop Test responses was 72% in this population (Figure 2.11). The percentage of children with stable eye movements was higher (88%). The large difference in the proportion of children with stable eye movement control in the normal population and in the reading disabled population is clearly worth further investigation. Correspondence between Dunlop test results and eye movement assessment was highest in this population at 87.3%.

Thus overall, of 473 children assessed by both the Dunlop test and eye movement monitoring of vergence eye movements, 359 (75.9%) children had corresponding results on the two tests. This level of correspondence was maintained in three groups: clinical, normal and reading disabled populations.

2.3.2 - Vergence Responses in Normal and Dyslexic Children

Table 2.1 compares the responses of 80 children from the general population (group 3) with 74 dyslexic children (group 2). The children were all assessed using the Similarities and Matrices subtests and the word reading test of the BAS. The dyslexic children were not pre-selected in any way. Hence, this group contained both 'visual' and 'auditory' dyslexics. All children were given the Dunlop Test and the results were scored as the number of times the non-reference eye saw a post move. Hence, if a child saw movement of the post seen by the left

PRIMARY SCHOOL CHILDREN

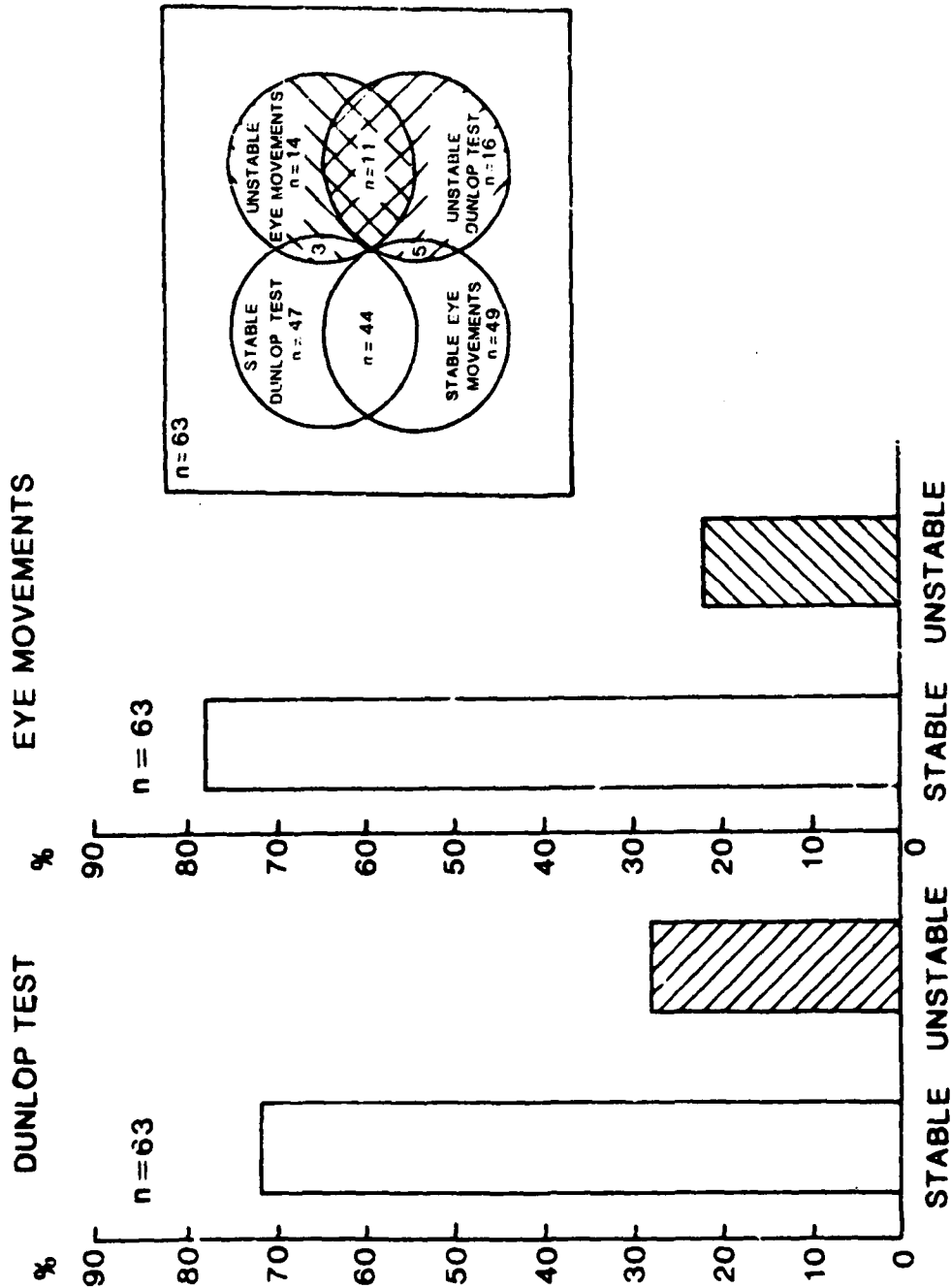


Figure 2.11 - Concordance between the results of the Dunlop Test and categorisation of eye movement recordings in a school population. The bar graphs on the left show the percentage of children classified as stable or unstable according to the Dunlop Test and vergence eye movement recordings. The Venn diagram on the right shows the distribution of the children into the four categories -

- i) Stable Dunlop Test responses and stable eye movements (n = 44).
- ii) Stable Dunlop Test responses and unstable eye movements (n = 3).
- iii) Unstable Dunlop Test responses and stable eye movements (n = 5).
- iv) Unstable Dunlop Test responses and unstable eye movements (n = 11).

eye 7 times and movement of the post seen by the right eye only 3 times, s/he would score 3. The more variable the response to the Dunlop Test, therefore, the higher the recorded score.

Table 2.1

		n	Mean	S.E.	T	p >
Age:	Dyslexic	74	9,3	,2	-0.88	0.38
	Normal	80	9,5	,2		
Sim.:	Dyslexic	74	51.15	0.71	-0.69	0.49
	Normal	80	51.85	0.72		
Mat.:	Dyslexic	74	49.24	0.83	-2.99	0.003
	Normal	80	52.60	0.75		
RACA:	Dyslexic	74	-26.4	1.3	-20.93	0.0001
	Normal	80	18.5	1.7		
D.T.:	Dyslexic	74	2.46	0.23	3.98	0.0001
	Normal	80	1.26	0.19		
DTD.:	Dyslexic	74	1.71	0.16	-2.39	0.018
	Normal	80	2.25	0.15		
DTC.:	Dyslexic	74	5.68	0.88	-0.38	0.70
	Normal	80	6.07	0.59		
SFD.:	Dyslexic	74	1.82	0.18	-4.36	0.0001
	Normal	80	2.85	0.14		
SFC.:	Dyslexic	74	8.74	0.84	-1.24	0.22
	Normal	80	10.09	0.68		
Rdot:	Dyslexic	74	41.69	3.31	4.98	0.0001
	Normal	80	24.19	1.19		

Table 2.1 - Comparison of Dunlop Test, Eye Movement and IQ scores for dyslexic and normal children. Key: D.T. - Dunlop Test, DTD - Degrees divergence during Dunlop Test, DTC - Degrees convergence during Dunlop Test, SFD - Degrees divergence using small rabbit slides, SFC - Degrees convergence using small rabbit slides, Rdot - Secs of arc stereopsis using Randot Test, Sim. - similarities, Mat. - Matrices, RACA - Reading age - chronological age in months

All children had their eye movements recorded during both convergence and divergence movements of the synoptophore tubes using the Dunlop Test slides and the small (macular) rabbits. The number of

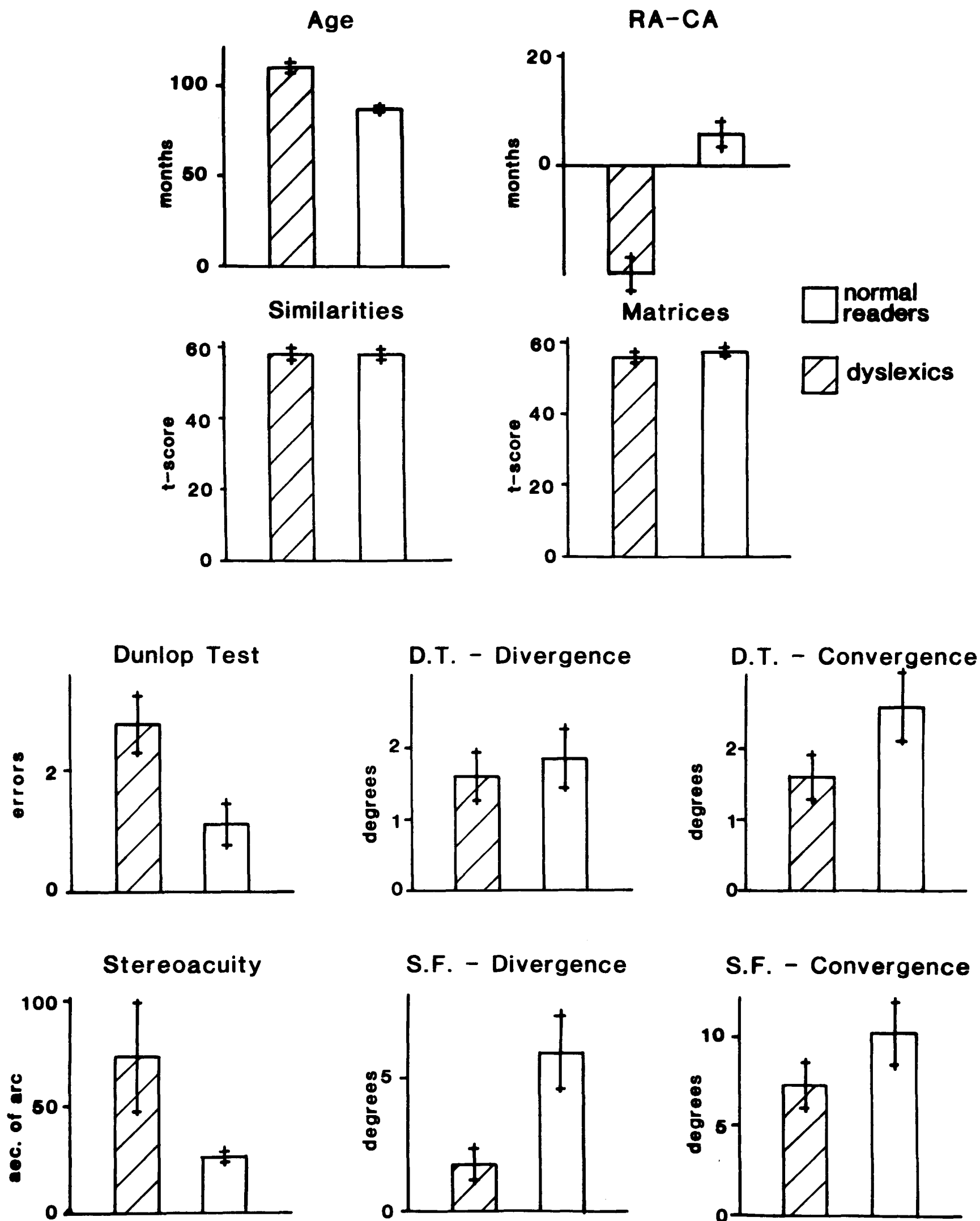


Figure 2.12 - Bar charts comparing 74 dyslexic children with 80 normal readers on measures of IQ, reading ability and eye movement control. Standard error bars are displayed.

degrees of vergence movements was measured from each trace.

Stereoacuity was measured using the Randot test for all children (see methods).

As can be seen from Table 2.1 and Figure 2.12, several differences which reached statistical significance were evident when the results for the two groups were compared. The dyslexic children scored significantly higher in the Dunlop Test than the normal readers, suggesting that they were less consistent in their responses. There was also a significant difference between the two groups in the amount of divergence achieved in response to both the Dunlop Test and the small fusion slides. Thus, the normal children were able to control their fusion for a greater range of divergence of the synoptophore tubes. Although normal children also produced more convergence to both Dunlop and small fusion slides, these results did not reach statistical significance.

There was a large difference in the ability of the two groups to detect small depth cues in the Randot test. The dyslexic group required disparities which were nearly twice the size of those seen by normal children before they were able to reliably detect depth (41.7 secs of arc for the dyslexic group compared with 24.2 secs of arc for the normal children). Of the two IQ subtests, no difference was found between the groups on the verbal test (Similarities). However, the visuospatial subtest (Matrices) was performed significantly worse by the dyslexic children. This is in accord with the findings of Thomson (1982). However, he found that the Matrices sub-test was the worst of the tests which differentiated between dyslexics and normal readers. Finally, a large difference was found when the reading ability of the two groups was compared. Whereas the children from the normal population had a reading age which was on average 18 months in advance

of their chronological age, the dyslexic children showed a deficit of over 2 years.

This analysis suggests that there was a difference between the ability of dyslexic and normal children to accurately control their vergence movements in response to pure retinal disparity cues. This ability seems to be associated with the stability of responses to the Dunlop Test. However, this does not prove that the dyslexic children were poorer at reading as a result of this deficit, since these groups were matched by age and not by reading ability. It is necessary to exclude the possibility that the effects were due to the differences in reading experience between the two groups before a causative role can be ascribed to the poor vergence control. A further analysis of 30 matched pairs from the above group was therefore performed.

2.3.3 - Vergence Responses in Reading Age Matched Subjects

In order to compare the results of the Dunlop Test and eye movement responses of normal and dyslexic children with similar reading experience, the dyslexic children were matched with normal children not on the basis of their chronological age but on the basis of IQ and reading age. Thus any differences which were found between the dyslexics and the normal readers could not be attributed to differences in reading experience. The reading age match was required to be within 3 months and the IQ match within 5 points. This matching process produced 30 pairs in total. Since some of the children from the 'general' population selected by this procedure had a similar reading age to their dyslexic pair, and were of a similar age (i.e. could be considered dyslexic), the matched pairs were divided into two groups. The reading age of the children from the general population was compared with their IQ score. The first group contained 20

dyslexics matched to younger children from the general population who were reading at or above their age level. Children from the general population who proved to have a reading age more than 2 SDs below that expected from their IQ formed another group of 10 matched pairs. This group therefore contained dyslexics from an unselected population matched with dyslexics of similar age from the clinical population. Thus in all cases the level of reading experience in the pairs was similar.

If the measures of vergence control discussed previously have a causal relationship with reading ability, the dyslexic-dyslexic matched pairs should perform similarly on these measures, whereas the dyslexic-normal pairs should show differences, with the normals performing better on the vergence tests. If, however, the differences between dyslexics and normals reported in the previous section were due to the different reading experience of the two groups, both the dyslexic-dyslexic and the dyslexic-normal groups should perform similarly on the tests.

Table 2.2 shows the comparison between the study dyslexics and the younger normal readers.

Table 2.2 and Figure 2.13 show the comparison between dyslexics matched with normal younger readers. Stein, Riddell and Fowler (1986) showed that there was a developmental trend with more young children showing unstable Dunlop Test responses. Hence, the younger normal readers might be expected to perform worse than older dyslexics. However, all the trends show that the younger normal readers have better vergence control than dyslexics matched for equivalent reading experience. The statistical significance reaches 99% for the Dunlop Test and convergence using the Dunlop Test slides. There is a 90% significant difference in the divergence using small fusion slides and

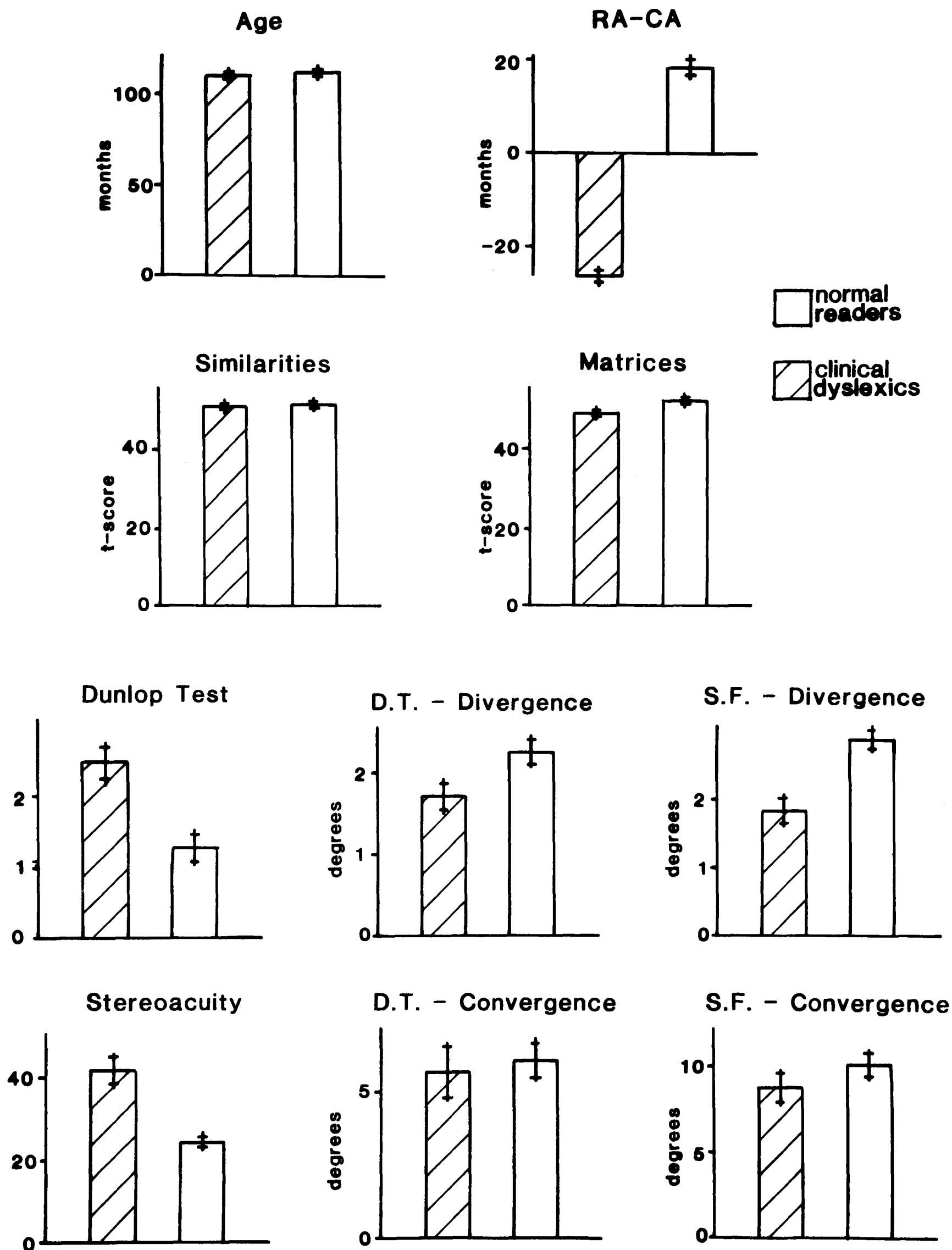


Figure 2.13 - Bar charts comparing 20 dyslexic children with 20 normal readers matched for reading age and IQ on measures of IQ, reading ability and eye movement control. Standard error bars are displayed.

in stereopsis. These results should be tested using a larger sample, which might demonstrate clearer differences between the two groups. However, the results do suggest that poor vergence control does have a causal relationship with reading difficulties since differences in these measures remain after the level of reading experience and IQ have been controlled.

Table 2.2

		n	Mean	S.E.	T	p >
Age:	Dyslexic	20	9,2	,3	6.41	0.0001
	Normal	20	7,2.5	,1.5		
Sim.:	Dyslexic	20	57.7	1.71	0.13	0.89
	Normal	20	57.4	1.48		
Mat.:	Dyslexic	20	55.7	1.57	-0.72	0.47
	Normal	20	57.1	1.24		
RACA:	Dyslexic	20	-19.7	3.10	-6.66	0.0001
	Normal	20	5.8	2.24		
D.T.:	Dyslexic	20	2.75	0.47	2.82	0.008
	Normal	20	1.1	0.34		
DTD.:	Dyslexic	20	1.6	0.34	-0.46	0.65
	Normal	20	1.85	0.42		
DTC.:	Dyslexic	20	1.75	0.59	-2.80	0.009
	Normal	20	5.95	1.38		
SFD.:	Dyslexic	20	1.6	0.32	-1.74	0.09
	Normal	20	2.6	0.48		
SFC.:	Dyslexic	20	7.3	1.28	-1.42	0.16
	Normal	20	10.35	1.72		
Rdot:	Dyslexic	20	73.5	25.4	1.84	0.08
	Normal	20	26.5	2.6		

Table 2.2 - Comparison of Dunlop Test, Eye Movement and IQ scores for dyslexic-normal matched pairs. Key: D.T. - Dunlop Test, DTD - Degrees divergence during Dunlop Test, DTC - Degrees convergence during Dunlop Test, SFD - Degrees divergence using small rabbit slides, SFC - Degrees convergence using small rabbit slides, Rdot - Secs of arc stereopsis using Randot Test, Sim. - similarities, Mat. - Matrices, RACA - Reading age - chronological age in months

The results of the comparison between the dyslexic-dyslexic group

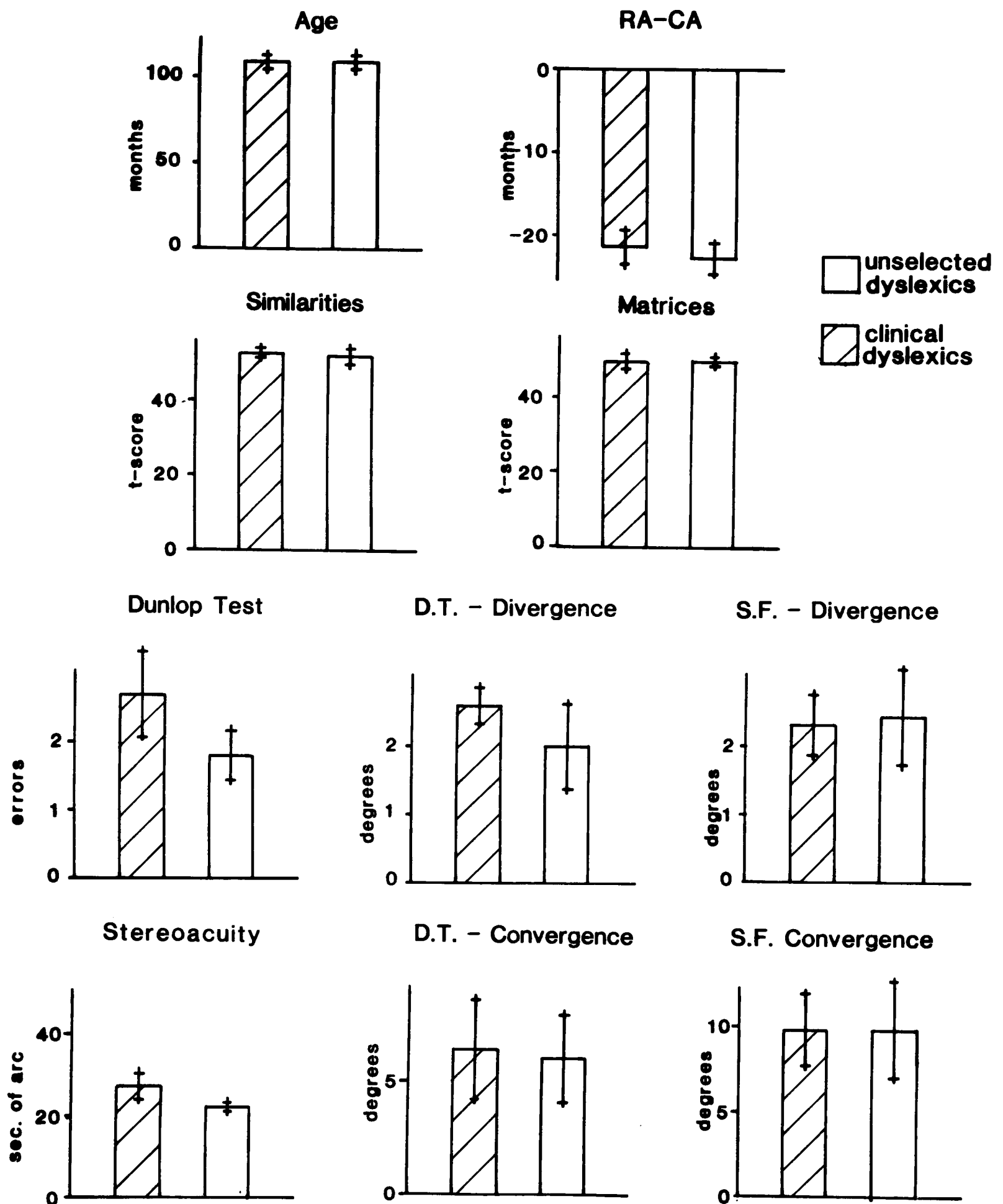


Figure 2.14 - Bar charts comparing 10 clinical dyslexic children with 10 dyslexic children from the normal school population. The clinical dyslexics are matched by reading age and IQ with the dyslexics from the normal population. Measures of IQ, reading ability and eye movement control are compared. Standard error bars are displayed.

The results of the comparison between the dyslexic-dyslexic group are shown in Table 2.3.

Table 2.3 and Figure 2.14 demonstrate that there are no significant differences between the dyslexic group from the clinical population when compared to those from the unselected population. In fact, in about half the measures of vergence control, the unselected group performed even worse than the dyslexics. Hence, all children with reading difficulties performed similarly on measures of vergence control regardless of whether they were referred clinically or discovered in the normal population.

These results were subjected to a second analysis using the definitions given in sections 2.2.3 & 4 to determine whether the responses to the Dunlop Test and the eye movements were stable. A χ^2 analysis was then performed to determine whether there was a statistically significant difference in the distribution of stability between the dyslexic population matched with either dyslexics or younger normal readers.

Figure 2.15 shows the results of this analysis. There were no significant differences between the two dyslexic populations on either Dunlop Test or eye movement stability ($\chi^2 = 1.82$, DoF = 1, $p < 0.50$ and $\chi^2 = 0$, DoF = 1, $p > 0.5$ respectively). However, there were statistically significant differences between the dyslexics and the normal readers in both stability of Dunlop Test responses and vergence eye movement control. In both instances, the younger normal readers are more likely to be stable ($\chi^2 = 8.64$, DoF = 1, $p < 0.01$ and $\chi^2 = 19.78$, DoF = 1, $p < 0.001$). Hence, this analysis also demonstrated that unstable Dunlop Test responses and the poor vergence control associated with them are not the result of a paucity of reading experience but are probably the cause of the reading difficulty.

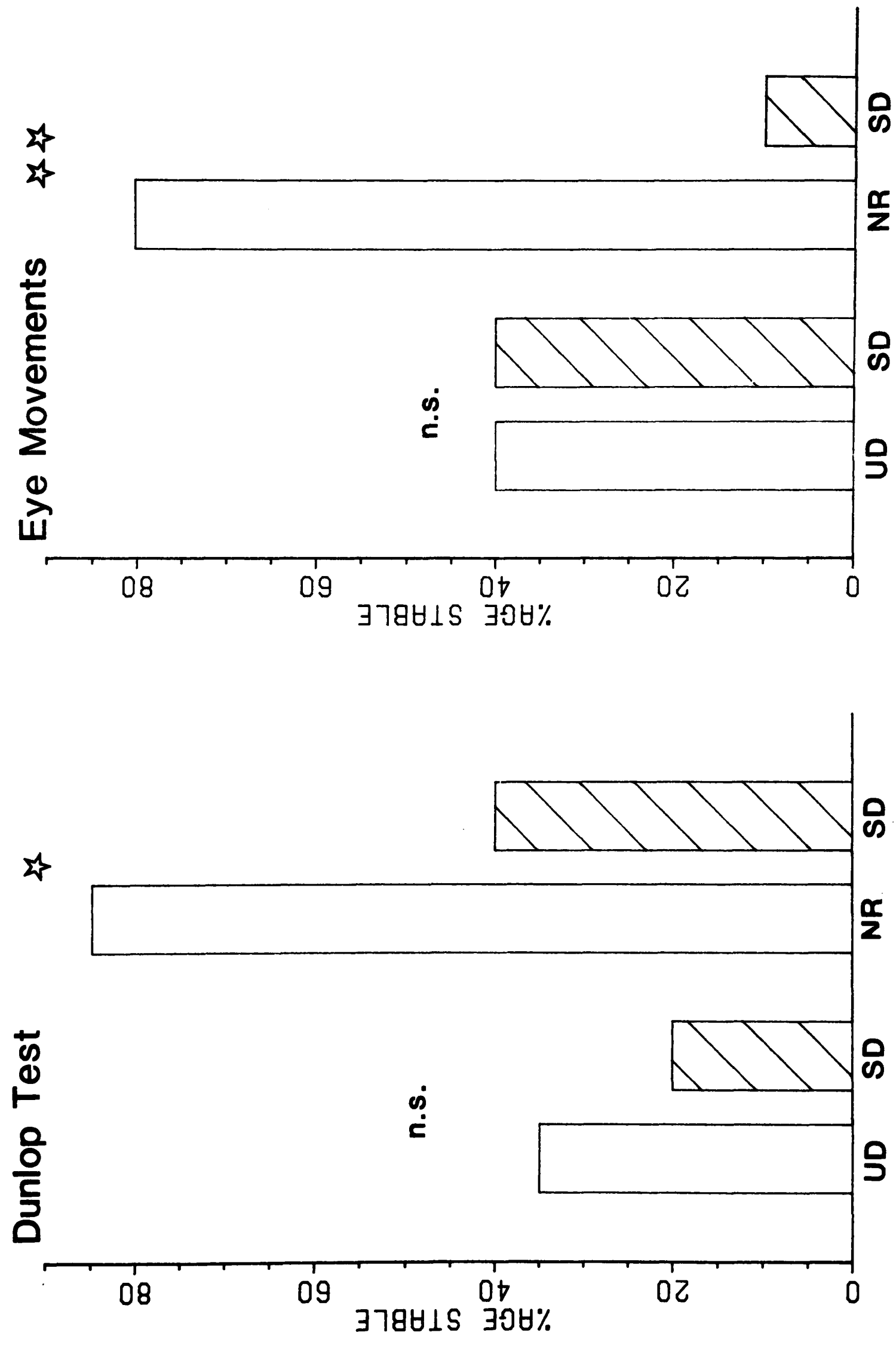


Figure 2.15 - Bar charts comparing the proportion of dyslexics and reading matched normal children with stable Dunlop Test responses and stable vergence eye movement control.

UD - unselected dyslexics
SD - study dyslexics
NR - normal readers

Table 2.3

		n	Mean	S.E.	T	p >
Age:	Dyslexic	10	9,1	,4	-0.16	0.87
	Normal	10	9,2	,4		
Sim.:	Dyslexic	10	52.6	1.29	0.31	0.76
	Normal	10	51.8	2.21		
Mat.:	Dyslexic	10	49.6	2.10	-0.12	0.91
	Normal	10	49.9	1.38		
RACA:	Dyslexic	10	-21.4	2.07	0.49	0.62
	Normal	10	-22.8	1.91		
D.T.:	Dyslexic	10	2.7	0.63	1.24	0.24
	Normal	10	1.8	0.36		
DTD.:	Dyslexic	10	2.6	0.27	0.87	0.39
	Normal	10	2.0	0.63		
DTC.:	Dyslexic	10	6.4	2.22	0.13	0.89
	Normal	10	6.0	1.94		
SFD.:	Dyslexic	10	2.3	0.45	-0.12	0.91
	Normal	10	2.4	0.70		
SFC.:	Dyslexic	10	9.8	2.15	0.00	1.00
	Normal	10	9.8	2.85		
Rdot:	Dyslexic	10	27.0	3.26	1.45	0.175
	Normal	10	22.0	1.10		

Table 2.3 - Comparison of Dunlop Test, Eye Movement and IQ scores for dyslexic-dyslexic matched pairs. Key: D.T. - Dunlop Test, DTD - Degrees divergence during Dunlop Test, DTC - Degrees convergence during Dunlop Test, SFD - Degrees divergence using small rabbit slides, SFC - Degrees convergence using small rabbit slides, Rdot - Secs of arc stereopsis using Randot Test, Sim. - similarities, Mat. - Matrices, RACA - Reading age - chronological age in months

2.3.4 - Target Size and Vergence Control

Three different sizes of fusion slides (7, 3 and 1 degree) were used to investigate the effect of target size on vergence control in the synoptophore (Figure 2.7). Previous results had suggested that the smaller the target, the poorer the vergence response for both normal and dyslexic children. However, this had been tested using slides with

EFFECT OF TARGET SIZE ON FUSIONAL AMPLITUDE

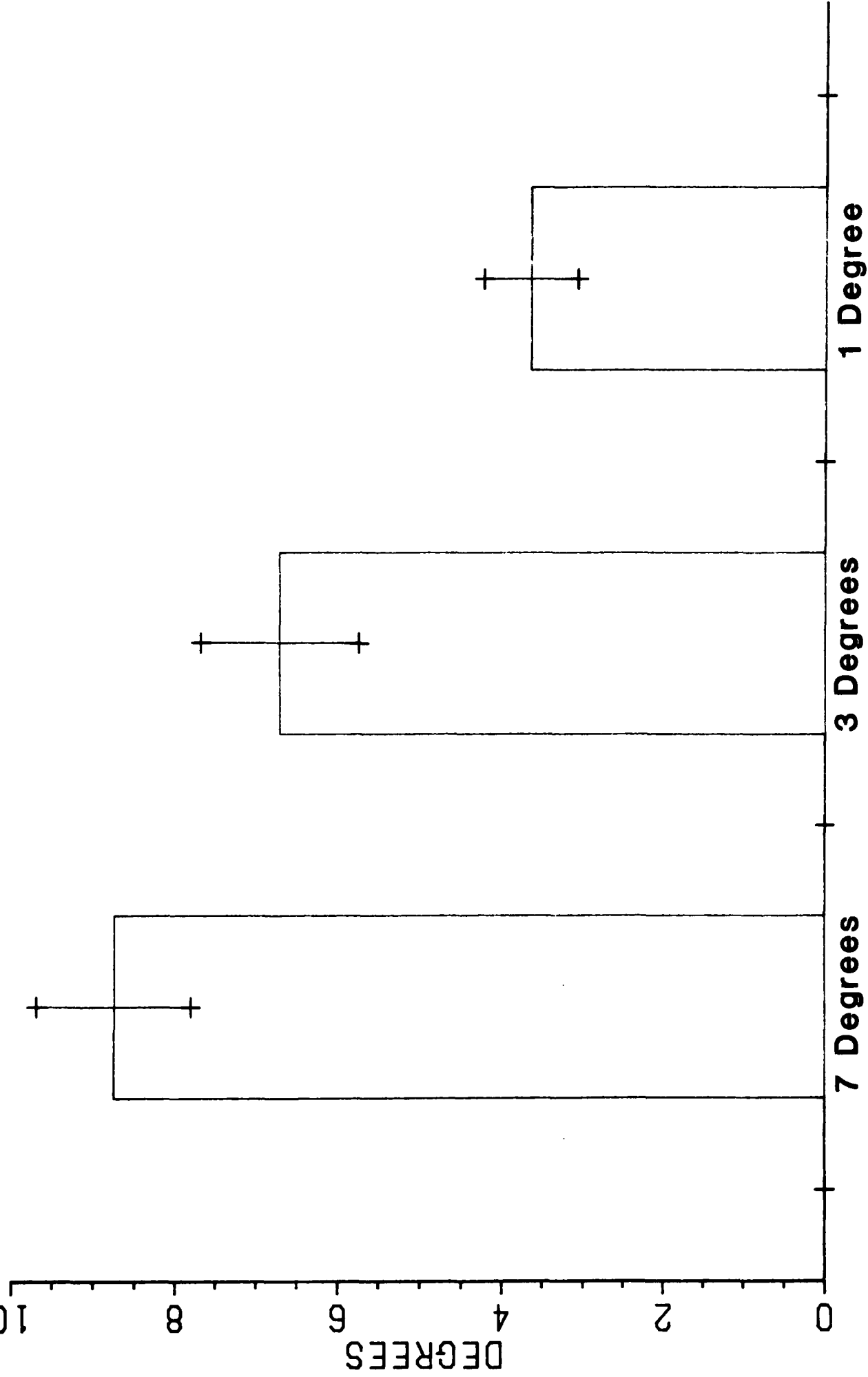


Figure 2.16 - Bar chart showing the effect of changing the size of the fusional target on the amplitude of fusion measured during convergence. Targets of 7 degrees, 3 degrees and 1 degree were tested at a speed of 0.6 degs/sec. The results show the average of 39 children's responses. Standard error bars are displayed.

different pictures. Hence, the difference in response might have been due to differences in the amount of detail in the pictures. This might have stimulated accommodation by different amounts which would in turn effect vergence responses. To control for this, slides showing the same picture, but varying in size, were used to test for the effect of size on the vergence response.

Each slide consisted of a circular outline and a central fixation point, but one slide from each pair showed a hatched area to one side while the other slide showed a dotted area on the other side. These areas acted as controls to ensure binocularity was maintained throughout the test. Thirty-nine normal readers (group 3) were used as subjects for this experiment.

Figure 2.16 shows the results of measuring the ability to maintain fusion during convergence using the three slide sizes. As the size of the slide was increased, the range over which children were able to maintain fusion also increased. Hence, the change in the ability to control vergence responses seen earlier was probably a property of the size of the slide used, and not of any accommodation effects.

Eight of the sample of children were found to have unstable Dunlop Test responses. The children were accordingly classified on the basis of their Dunlop Test responses. Table 2.4 and Figure 2.17 show the results of this analysis. Although there was a trend for children with unstable reference to have lower amplitude of fusion for all target sizes, this difference only reached statistical significance with the smallest target used. This re-emphasises the importance of testing dyslexic children for poor vergence control using small targets.

EFFECT OF TARGET SIZE ON FUSIONAL AMPLITUDE

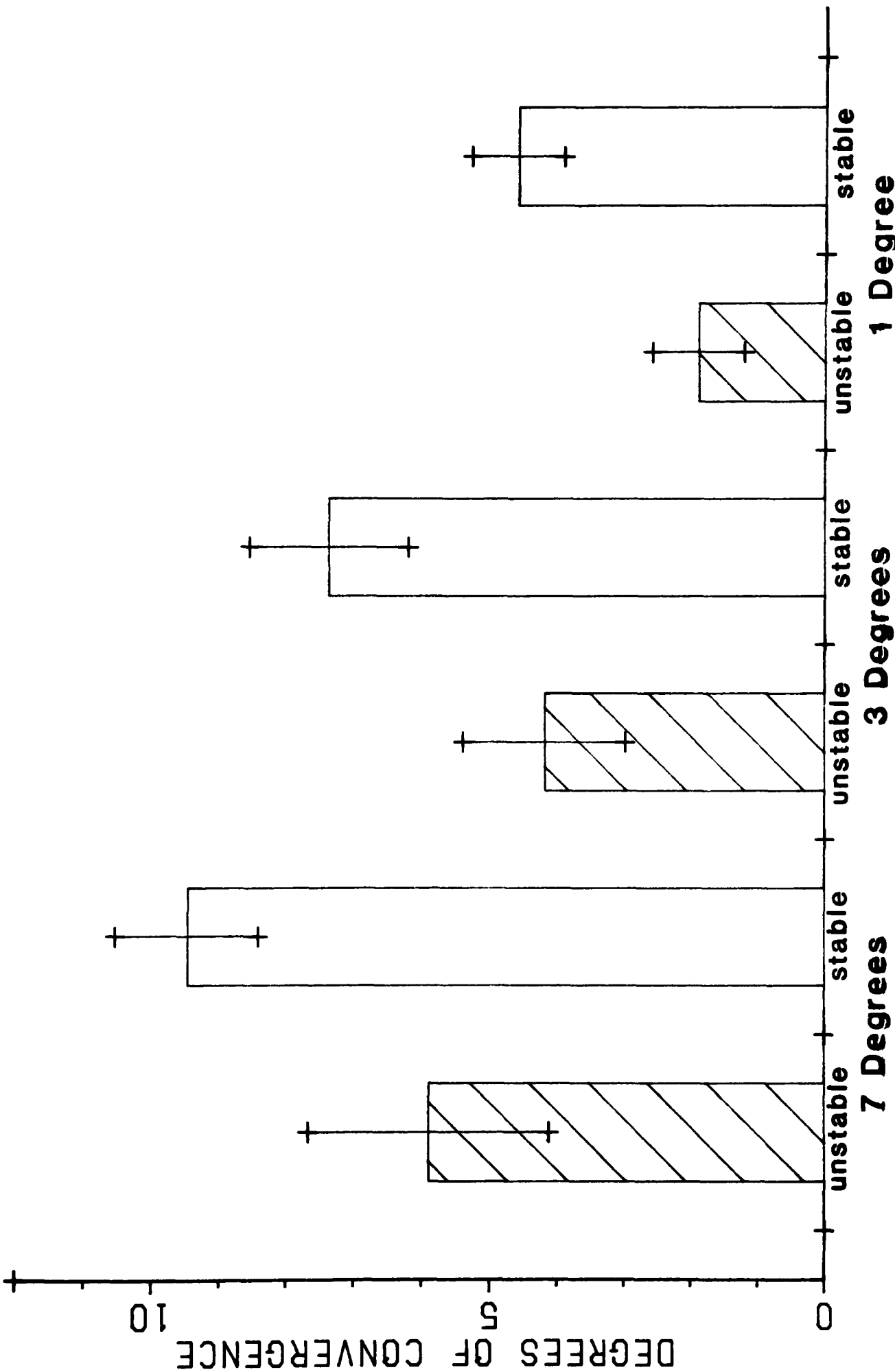


Figure 2.17 - Bar charts showing the effect of changing target size on fusional amplitude for 31 children with stable Dunlop test responses compared with 8 children with unstable responses. Target sizes and speed are as above. Standard error bars are displayed.

Table 2.4

Stable (n = 31)			Unstable (n = 8)			
Target Size	Mean	S.E.	Mean	S.E.	t	p <
7 degrees	9.5	1.06	5.9	1.78	1.60	0.12
3 degrees	7.4	1.18	4.2	1.21	1.30	0.20
1 degree	4.6	0.68	1.9	0.69	1.98	0.05

Table 2.4 - Amplitude of vergence eye movement responses in degrees for each of three target sizes recorded in 31 children with stable responses in the Dunlop Test and 8 children with unstable responses.

2.3.5 - Target Speed and Vergence Control

The effect of varying the speed with which the retinal disparity changed during convergence on the amplitude of fusion was also investigated. The smallest fusion target (Red Indian) was used for these studies. The subjects for this were 28 children from the normal population (group 3) and 19 dyslexic children (group 2).

The combined data for all 47 children is shown in Figure 2.18. This shows that as the speed of the vergence movements of the synoptophore tubes was increased, the average amplitude of fusion decreased. Hence, it seems that all children found it more difficult to track a target moving in simulated depth at 1.4 degs./second than when the target moved more slowly (0.3 degs./second).

The children were then divided by their score on the Dunlop Test. There were 31 children classified as having stable responses and 16 children with unstable responses. The amplitude of fusion recorded at each speed of target movement was averaged for each group. Figure 2.19 and Table 2.5 show the results of this analysis.

The data in Table 2.5 show that, at all but the slowest speed tested, children with unstable responses to the Dunlop Test had

EFFECT OF TARGET SPEED ON FUSIONAL AMPLITUDE

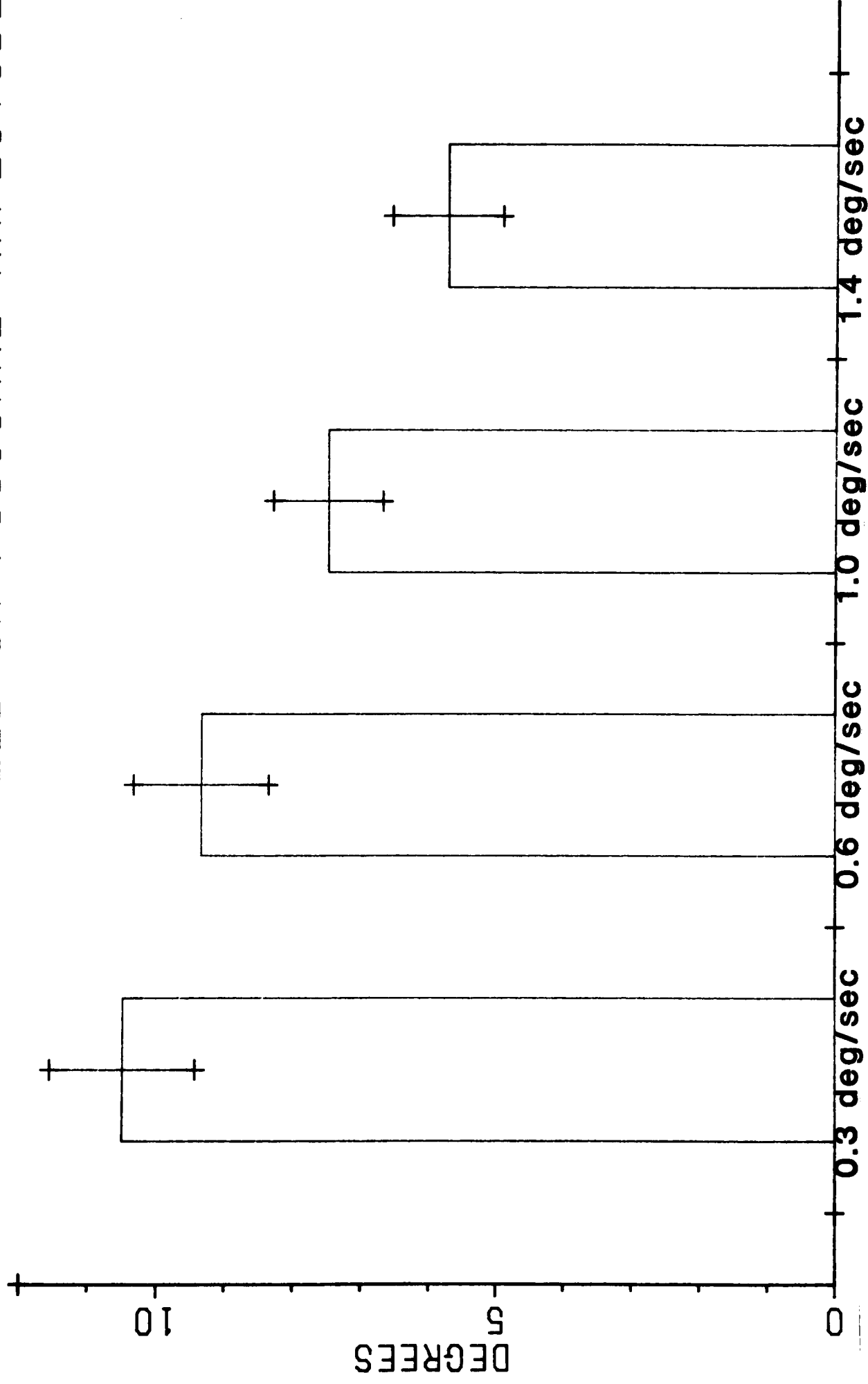


Figure 2.18 - Bar charts showing the effect of changing the speed at which the synoptophore tubes were converged on fusional amplitude. The Red Indian fusion slides were used as a foveal target. Speeds of 0.3 degs/sec, 0.6 degs/sec, 1.0 degs/sec and 1.4 degs/sec were tested. Results are the averaged responses from 47 children. Standard error bars are displayed.

EFFECT OF TARGET SPEED ON FUSIONAL AMPLITUDE

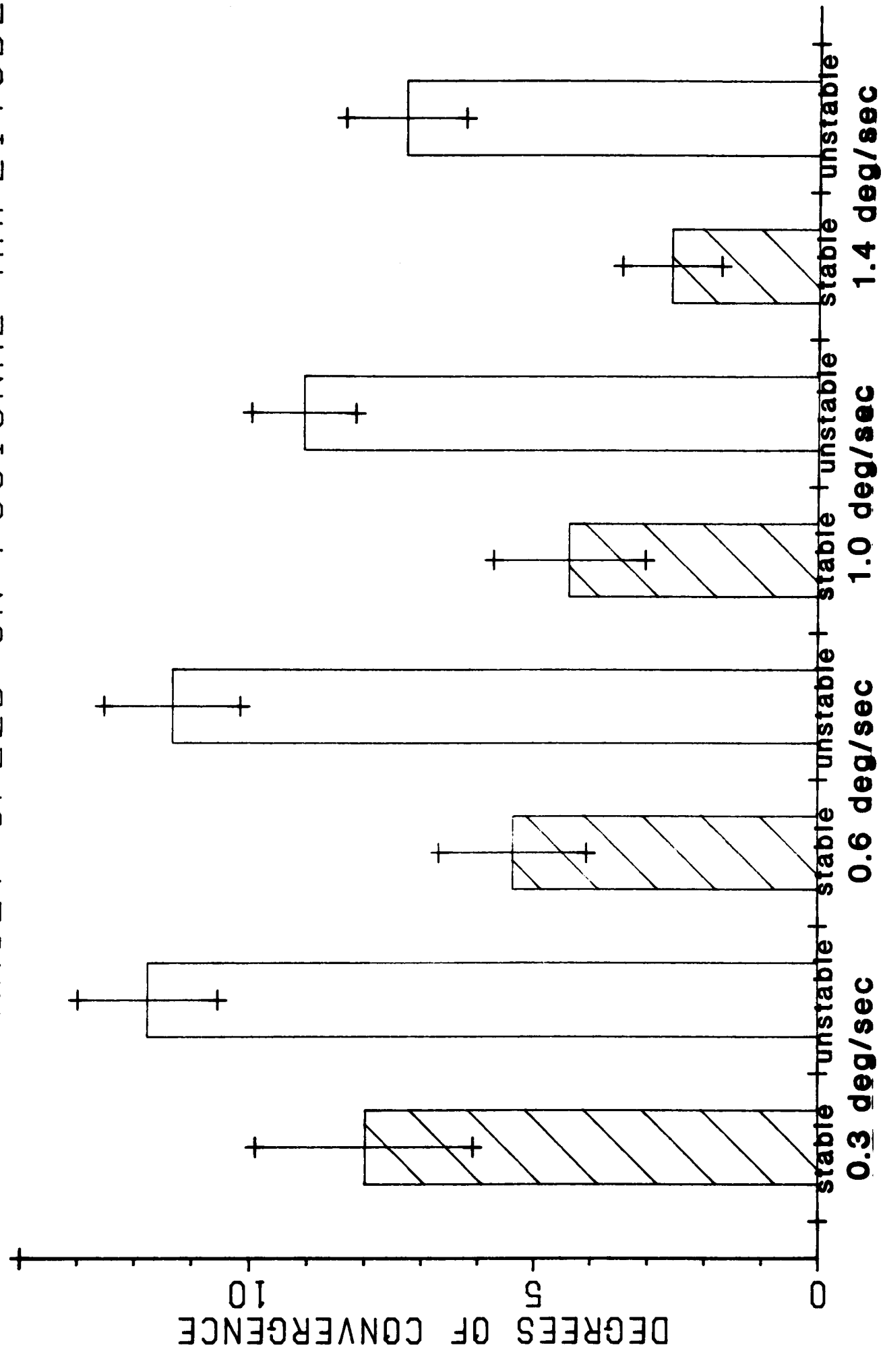


Figure 2.19 - Bar charts showing the effect of changing the speed of convergence on fusional amplitude. The results show the averaged responses from 31 children with stable Dunlop Test responses compared with 16 children with unstable responses. Target speeds and size are as above. Standard error bars are displayed.

significantly poorer vergence responses than children with stable reference. The greatest difference between children with stable compared with unstable responses was found at 0.6 degs/second. This is the speed at which the Dunlop Test and other measures of vergence stability are normally performed. This data emphasises the difference in control of vergence movements found between children with stable versus unstable responses in the Dunlop Test.

Table 2.5

Stable (n = 31)		Unstable (n = 16)		t	p <
Speed	Mean	S.E.	Mean		
0.3degs/sec	11.8	1.22	8.0	1.74	0.09
0.6degs/sec	11.4	1.19	5.4	3.13	0.003
1.0degs/sec	9.1	0.91	4.4	2.92	0.005
1.4degs/sec	7.3	1.06	2.6	2.94	0.005

Table 2.5 - Amplitude of fusion in degrees for each of four target speeds recorded using small fusion slides in 31 children with stable responses to the Dunlop Test and 16 children with unstable responses.

2.4 - Discussion

The results presented in this chapter demonstrate that there is a high concordance between the results of the Dunlop Test in normal and dyslexic children and their ability to produce accurately controlled vergence eye movements in response to pure retinal disparity cues. Both measures suggest therefore that some children with reading difficulties suffer from poor binocular control during disconjugate eye movements. This is shown both by the instability of their responses in the Dunlop Test, when the children seemed unable to consistently use one eye for assessing visual direction, and by their inability to respond to changes in retinal disparity of small targets

with accurate disconjugate tracking movements of the eyes.

In order to link this poor binocular control to failure in the ability to learn to read, it is necessary to compare the abilities of children matched for chronological age and for reading age on tests of binocular control. When 74 dyslexics were compared to 80 normal children of the same chronological age, significant differences were found between the two groups in several measures of vergence control. The dyslexic children showed greater instability in their responses to the Dunlop Test, poorer amplitude of fusion during divergence of both the Dunlop Test slides and a smaller fusion slide, and poor stereopsis. Another measure of vergence control, namely the amplitude of fusion during convergence movements when a small fusion slide was used, was also poorer in the dyslexic group, but this difference did not reach statistical significance. The mixture of stable and unstable responses found in the Dunlop Test and eye movement recording within the dyslexic population will also decrease the chances of finding statistically significant differences between normal readers and dyslexics.

The dyslexic group also showed poorer scores on one sub-test of the BAS - the Matrices sub-test. In this test, the children are required to complete a matrix by comparing the designs on three squares and completing the pattern by filling in the last square. It could be argued that the children with reading difficulties were not affected by their poor vergence ability, but were only reading disabled because of their lower intelligence, demonstrated by their scores on this test. However, these children did not score significantly differently from the normal children on a second sub-test of the BAS, namely the Similarities sub-test. This test is purely verbal and is thought to give a better estimate of the IQ of dyslexic children (Thomson, 1982).

Another possible explanation for the lower scores of the dyslexic children on the Matrices test is that their poor vergence control also caused this test to be difficult. The task requires that the children move their eyes between several small patterns, noticing differences and similarities between their visual forms. If these children have poor eye movement control, this would prevent them from correctly locating the differences between patterns, thus causing them to score poorly on the test.

The analysis described above shows that dyslexic children scored significantly worse than normal children matched for age on several tasks involving accurate control of vergence eye movements. However, it could be argued that the normal children performed better on these tasks as a result of their greater reading experience. In order to rule out this possibility, 30 dyslexics from the clinical population were matched by reading age and IQ with 30 children from the general school population. Twenty of these pairs were matches between dyslexic children and younger normal readers. In these twenty pairs, significant differences were found between the dyslexics and the younger normal readers on several measures of vergence control. Specifically, the dyslexic children were more unstable in their responses to the Dunlop Test and showed smaller amplitude of fusion while converging during the Dunlop Test. They also tended to show poorer stereopsis, and smaller amplitude of fusion in both convergence and divergence with the small fusion slides. Thus the finding that dyslexic children were poorer in many facets of vergence control was confirmed even when reading experience and IQ were controlled for.

Further support for this result comes from comparing the remaining ten reading age matched pairs. In this case, the dyslexic children were matched with children of the same age from the general

population; however, the children from the general population were found to be as far behind in their reading age as the dyslexics. The same stringent criteria were used on these children to define them as dyslexic as were used for the selected study population. Hence, these children provided an unselected control group of dyslexics to compare with the clinical population. When this comparison was made, no differences were found between the groups in any of the measures of vergence control tested. This result rules out the possibility that the dyslexic children referred to the clinic were in some way pre-selected, and therefore more likely to show vergence problems than children in the general population.

The proportion of children with vergence problems in the two populations was also compared using the reading age matched pairs. This analysis showed that significantly more dyslexic children than younger normal readers were affected by problems of vergence control. No significant differences were found when the proportion of children with vergence problems was compared in the two dyslexic groups i.e. there were as many dyslexics from the normal population with problems of vergence control as had been found in the clinical population.

The results suggest that dyslexic children with problems of vergence control might be identified within the general population, and distinguished from other dyslexics, on the basis of amplitude of fusion measured on the synoptophore with Dunlop Test or small fusion slides. Poor stereopsis might be used as another useful indicator of vergence control difficulties. However, if the range of fusion during convergence is to be used as a measure of poor vergence control, slide sizes should be standardised and the speed of target movement should be clearly defined so that these results can be widely replicated.

In order to determine the most appropriate size and speed of target movement, a range of target sizes and speeds was used to assess the stability of vergence control on groups of unselected school children. The results of this showed that the amplitude of fusion decreased with increasing target speed and with decreasing target size. When the children were classified according to their scores on the Dunlop Test, into groups with poor or good vergence control, the greatest differences between the two groups were found for a target speed of 0.6 degrees/second and a target size of 1 degree. This optimum speed of target movement is the same as that used routinely for the Dunlop Test, and is the speed at which all the measurements comparing target size were made. This speed was originally chosen by a process of trial and error. The target size is slightly smaller than the smallest target used here (Red Indian - 1.5 x 2 degrees), and is also slightly smaller than the Dunlop Test target (25x 25degrees). However, these differences are small, and so these targets would still be expected to show near optimum differences between the normal and the vergence impaired groups.

Why should unstable vergence control lead to difficulty with learning to read? When Ogle (1962) described his experiments on fixation disparity, he suggested that this measurement could be used to determine which eye was being used, under binocular conditions, to determine the visual direction of objects in space. He argued that as the eyes are pointing in different directions when they are converged, each eye may attribute a slightly different position to objects in space, relative to the centre of their visual field. If objects are localised using first one eye and then the other as the reference point for calculation of visual direction, then objects can appear to move in space. A simple demonstration of this is obtained by holding

up a finger at a distance of about 30cms. If the finger is viewed with each eye alternately closed, there is an illusion of movement of the finger. When both eyes are open, the finger is seen in a position intermediate between these two points.

If first one eye, then the other, is being used to locate objects visually, then the stability of the visual world might be disturbed. Since there need be no movement of the eyes between these separate calculations of visual direction, there is no motor outflow to indicate that the change in apparent position is due to a shift in reference eye position. The change in direction might then be attributed to a movement of the object in space. Hence there may be disturbance of the stability of objects. This would be particularly obvious for small objects, such as letters in words, which could shift sufficiently to appear suddenly in the original position of another letter. Such shifts of reference point might affect the child's ability to determine the correct sequence of the letters in a word. These problems would trouble beginning readers particularly, since they need to use the exact sequence of letters in a word to enable them to identify new words through grapheme-phoneme correspondence. This ability is only required for unfamiliar words and non-words in adult readers. Hence in acquired dyslexia visual instability causes less severe problems.

Ogle's studies of fixation disparity suggested a link between visual direction sense and vergence control. The illusion of movement of a monocular target in a binocular field when the target is stationary is attributable to autokinetic movements. This apparent movement can be enhanced if the eyes are simultaneously moved in a disconjugate manner. In normal subjects, the apparent movement is always attributed to the same eye. This would suggest that the

positional signals from one eye only are used to determine the amount of movement across the retina which is attributable to the outside world, and the amount which is caused by movement of the eye itself.

The results presented here suggest that children with unstable responses to the Dunlop Test (which is analogous to Ogle's test of visual direction sense) are also impaired in their control of fine vergence eye movements. An instability of visual direction sense might impede the development of accurate vergence movements by disrupting the stable reference point necessary to determine the amount of vergence which is required to move from a near to a far target, or to track a target moving in depth. A change in eye position from one object of interest to a second requires a knowledge of the relative locations of the two objects, which in turn requires that both objects be referred to the same point when their respective visual directions are calculated. Children with unstable visual direction sense will find this difficult and so have poor ability to change eye position when small objects are involved, and the eyes are in a converged position (i.e. pointing in different directions).

This description of the problems which children with unstable visual direction sense and vergence control might have leads to the prediction that children with unstable responses in the Dunlop Test should be poorer than children with stable responses in a test involving the localisation of small objects in space. It is important that the targets studied are small, that the test is performed at a near position, so that the eyes are converged, and that the test involves no linguistic component, so that there is no possibility of children failing because they do not have the linguistic skills necessary to perform the test. The results of such studies are reported in the next chapter.

Chapter 3 - Spatial Discrimination Ability

3.1 - Introduction

In Chapter 2 results were presented which suggested that some reading disabled children fail to learn to read as a result of an inability to perform accurate fine vergence movements. This group were also more likely to have an unstable response when tested by the Dunlop test. If the Dunlop test responses result from the inability to control vergence movements accurately, then an important prediction is that children who fail the Dunlop Test ought to be less able to judge the position of small objects accurately in space.

Accurate vergence control is necessary in order to determine the position of small objects in space, as discussed earlier. When the eyes are converged to look at an object which is close to the viewer, the two eyes can potentially give different information about the position of the object in space. This can be easily shown by holding a finger at eye level about 10 cms away from the face. If first one eye and then the other is closed the finger appears to move in space. It seems that in order to tell where an object is in space, the brain associates the retinal information from one eye with the oculomotor information from that same eye, and uses this set of signals in order to calculate the object's position relative to the observer. If vergence control is not accurately maintained then oculomotor information from the eyes is even more essential to determine the relative position of objects in space. Consider the consequences of a small change in vergence angle intervening between the presentation of two small objects. In order to determine the position of these objects relative to one another it is necessary that the retinotopic co-ordinates defining the positions of these objects are integrated with

the oculomotor co-ordinates which define the size and direction of the intervening eye movement. If the objects are closer than optical infinity then the initial convergent position of the eyes must also be incorporated in the calculation of the relative positions. This calculation presents a complicated problem to the visuomotor integration system.

The results presented in the previous chapter show that children who have unstable responses in the Dunlop Test tend to have unstable vergence eye movement control. They cannot relate apparent movement of an object consistently with movement of one or other eye. It was suggested that in these cases there is a failure to associate the relevant retinotopic and visual information. Hence, children with unstable Dunlop Test responses might find it more difficult to calculate the relative position of small objects in space. This would cause serious difficulties for children who are learning to read since it would tend to affect the appearance of letters in words. The destabilisation would likely only affect small objects like letters, since intervening eye movements are small.

If this hypothesis is correct, then the children with unstable reference eye on the Dunlop test should be less proficient at tasks involving location of small objects accurately in space than children who have a stable reference eye. It is this prediction which is examined in the experiments described below. The hypothesis was tested by asking children to perform a task which required them to determine the position of a small spot (approx. 10' of arc). The child was required to fixate the priming spot for a short period, after which this spot was replaced by a similar test spot positioned slightly to the left or right of the priming spot position. The child was required to indicate on which side of the priming spot the test spot had

appeared. An error was scored if the child gave the wrong position of a priming spot with respect to a test spot. The children were also given the Dunlop test to determine whether they had yet developed a stable reference eye. It was predicted that the children with unstable reference eye would perform less well on this test of spatial discrimination than the children whose reference eye was fully developed.

The design of this experiment also gave an opportunity to examine the possibility of effects in either the right or the left visual field. Since the child was required to fixate a central priming spot and since the time between priming spot and test spot was of a short duration (200 msec), then if the child was in fact looking at the priming spot, visual information regarding the test spot appearing to the left of the priming spot would first be received by the right hemisphere and vice versa for a spot to the right of fixation. This is a direct result of the anatomy of the visual pathways (Figure 3.1). Both hemispheres will eventually receive information about each spot since fibres in the corpus callosum connect the visual cortices on each side. However, there is evidence to suggest that processing is faster and more accurate in the visual hemisphere which receives the visual information by the direct route (Springer and Deutsch, 1985). There are two possible explanations for the superior processing of the direct route. The first is that the quality of information is degraded during transfer across the corpus callosum. There will certainly be a short delay before the contralateral hemisphere can access the information. A second proposal is that only certain types of information are passed across the corpus callosum. It is suggested that the corpus callosum does not act to duplicate all sensory information in the two hemispheres, but selectively passes information

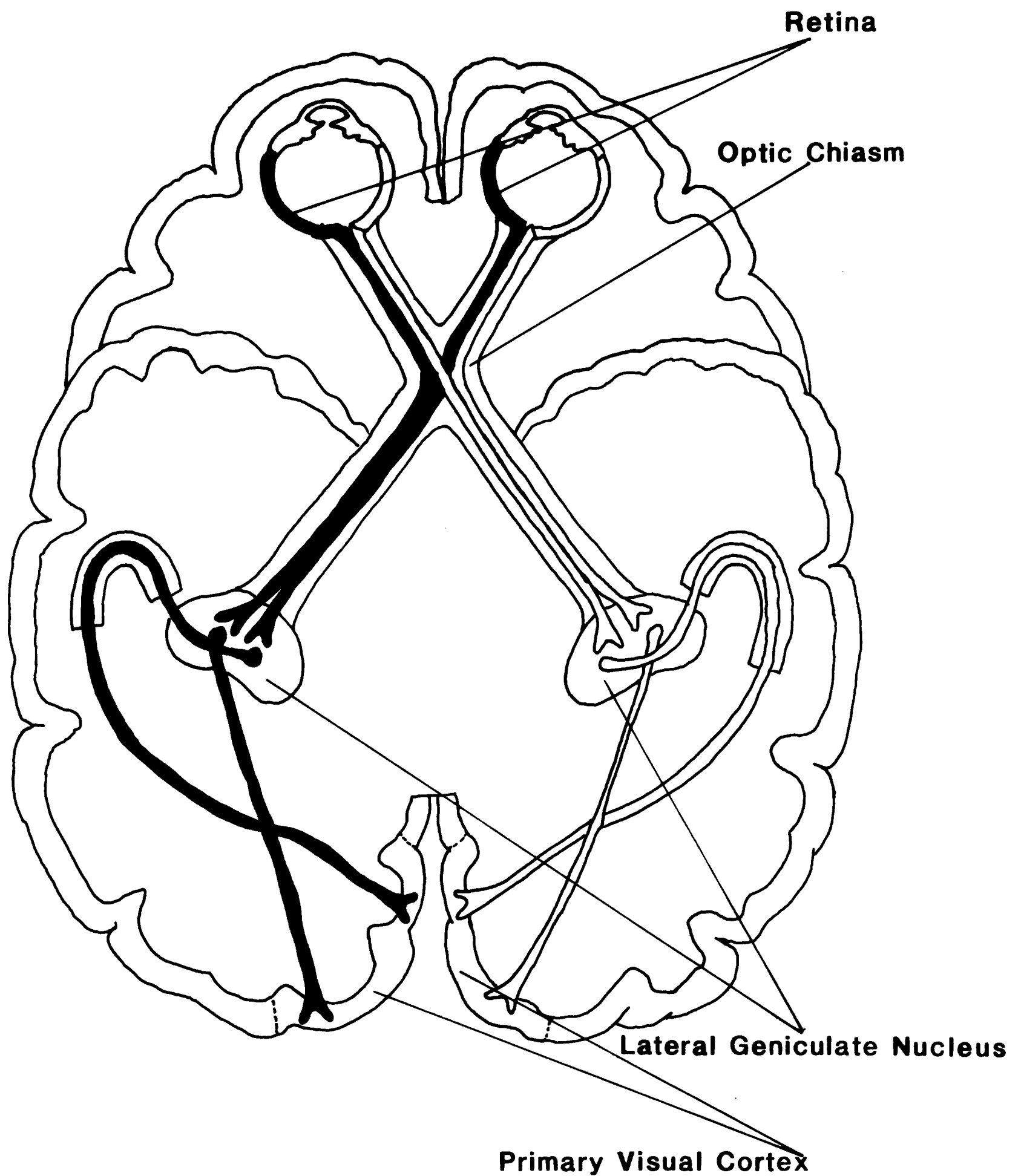


Figure 3.1 - Schematic diagram to show the decussation of the visual pathways at the optic chiasm. This ensures that objects to the left of the fixation point will be projected first to the right hemisphere while objects to the right of fixation will project to the left hemisphere.

from one hemisphere to the other in order to prevent duplication of processing. Whatever the explanation, the result is that information arriving in one hemisphere by the direct route is processed faster or more accurately than information arriving by the indirect commissural route.

This gives an opportunity of studying the ability of each of the hemispheres to process visuospatial information. In this experiment, for example, when the test spot was to the left of the priming spot, the information was processed primarily in the right hemisphere (LVF-RH condition), whereas a test spot to the right of the priming spot was preferentially processed in the left hemisphere (RVF-LH condition). By calculating the distribution of errors in the left and right visual fields, the ability of each of the hemispheres to perform this visuospatial task could be investigated.

Evidence using presentation of visual information to each hemisphere selectively has shown that the nature of the task is important in determining which of the two hemispheres performs better (Springer and Deutsch, 1985). Tasks involving language processing produce a left hemisphere superiority (Geffen, Bradshaw and Wallace, 1971) whereas tasks involving visuospatial processing are performed more accurately by the right hemisphere (e.g. Kimura, 1969). Since the experiment described here involves visuospatial processing, but no language processing, a LVF-RH advantage would be expected.

3.2 - Subjects and Methods

Two groups of children were used for this study:

- 1) a group of 80 children (average age: 9yrs 6mths) was tested in the orthoptic department of the Royal Berkshire Hospital in Reading. These children had all been referred to the department with

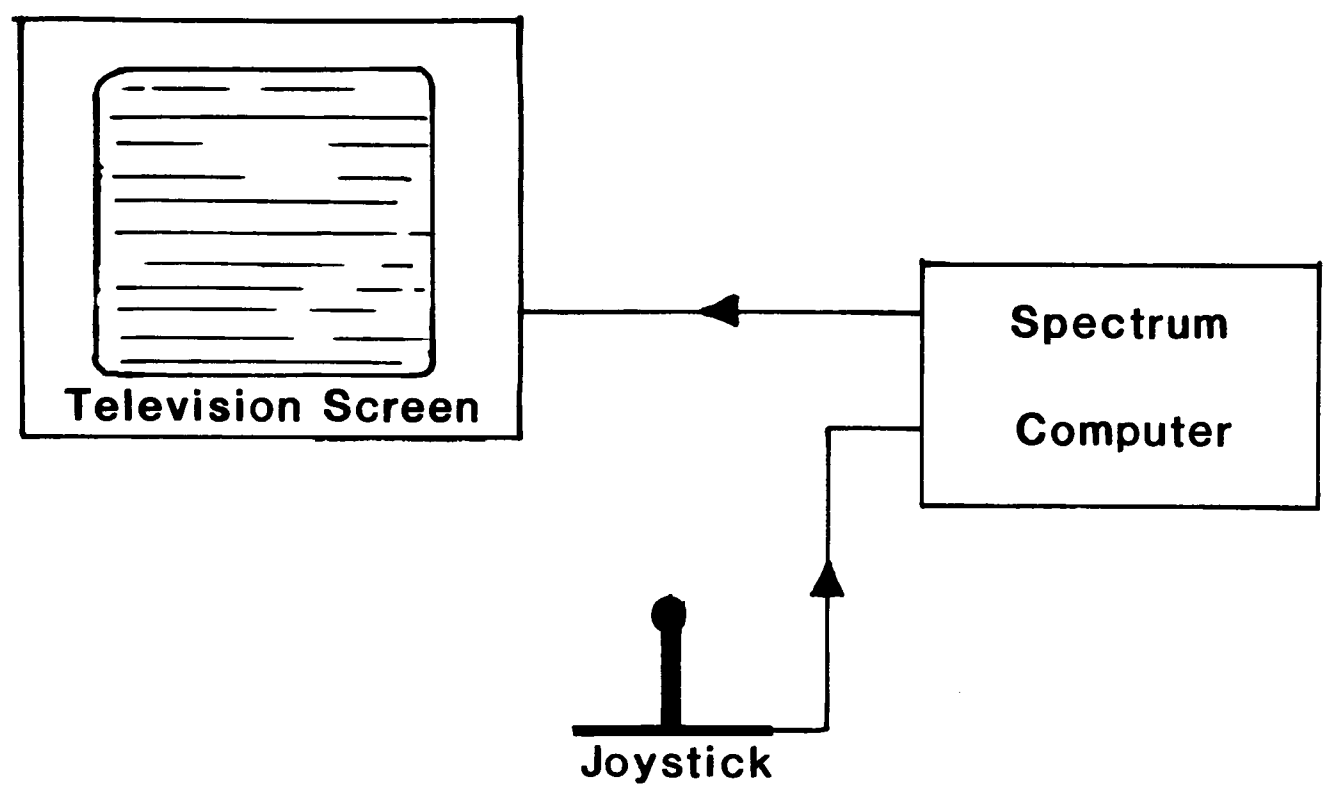


Figure 3.2 - Schematic diagram of the experimental apparatus used to test the spatial localisation ability of normal and reading disabled children.

difficulties in learning to read.

2) a group of 80 children (average age: 5yrs 6mths) was tested at Ascot Heath Infant School. These were normal children in their first two years of primary school education.

All children were assessed using the spatial discrimination test. This involved sitting about 30cm away from a T.V. monitor (Figure 3.2). The monitor was used to display a priming spot (9'30" x 19' of visual arc). The priming spot remained on the screen for 1 sec., which allowed the eyes to move, after which there was a delay of 200 msec before a test spot appeared to the left or the right of the priming spot position. The test spot remained on the screen for 100 msec (Figure 3.3). There were three possible distances between the priming spot and the test spot - 9'30", 19', and 28'30" of arc. Since the test spot could appear either to the left or the right of the priming spot, this gave six possible positions for the test spot. These were assigned arbitrary values - -3, -2, -1, 1, 2, and 3. Using three positions to left and right meant that the test was suitable for many abilities. The youngest children found all but the most distant position difficult, while the older children made all their errors at the near positions.

The relative positions of priming spot and test spot were randomised for both distance apart and direction during each test. The number of presentations at each possible position was kept as similar as possible within each test to ensure that there were no large discrepancies in the number of trials presented at each position between groups. Each block consisted of at least 20 trials.

The short delay between priming spot and test spot meant that there was an illusion of movement. This illusion was used to explain the nature of the test to the subjects. The subjects were asked to report

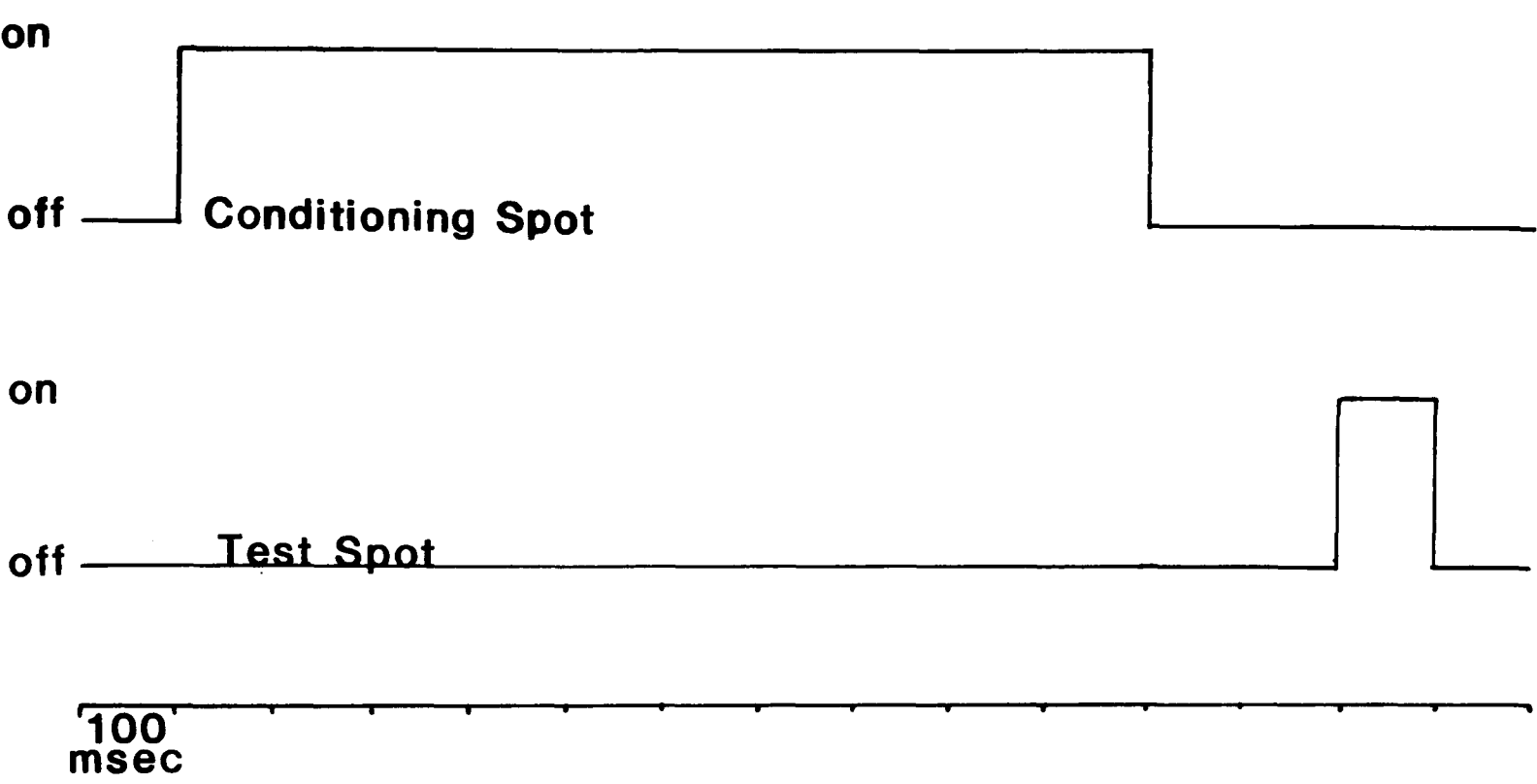


Figure 3.3 - Timing diagram showing the onset and duration of the conditioning and test spots used in the experiment.

in which direction they thought the spot had moved. The experimenter used a joystick to record the direction of movement indicated by the subject. The computer was used to control the experiment; then it was used to calculate whether the subject's response to each target was correct. A one was scored for a correct responses or a zero for an incorrect response. An error was recorded if the child reported that the test spot had appeared on the wrong side of the priming spot.

The timing of the experiment was controlled by the child. The start of a trial occurred a short time after the answer to the previous trial had been signalled by the experimenter. The child was encouraged to give an answer to all trials by pointing in the direction of perceived motion. This meant that the child was not required to differentiate between left and right nor was any speech or hand co-ordination involved.

Two test conditions were used in the experiment:

1) A square area (14.5 x 14.5 cm) was defined by a black borderline. The child was told that the spot would appear anywhere within this square. A random number generator was then used to produce the co-ordinates of the priming and target spot positions within this area. This condition is referred to as random left-right discrimination (RLRD).

2) In the second paradigm, the square area defined above was divided by horizontal lines 1 cm apart. This gave the impression of a lined page. The positions of the priming and test spots were then arranged so that the first trial was within a 1.5 cm portion on the left hand side of the first line. The portions were then moved sequentially to the right so that there were 10 trials per line. The test spot appeared randomly within each portion so that the distance between trials was random. After each set of 10 trials, the following

**Percentage errors on RLRD Task
Stable vs. Unstable**

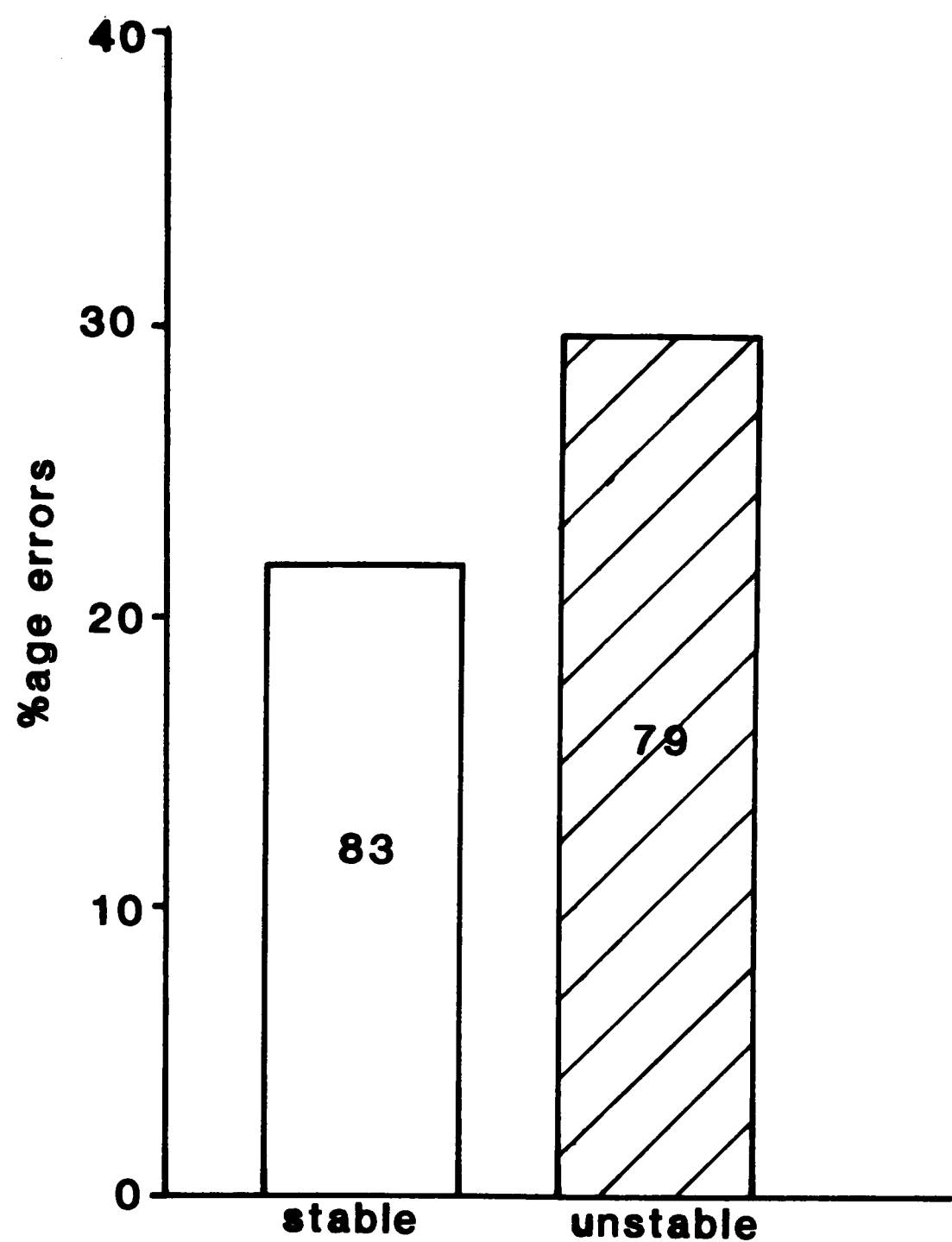


Figure 3.4 - Bar chart showing the percentage errors made by 83 children with stable Dunlop Test responses compared with those of 79 children with unstable responses on the RLRD task.

trial began on the right hand side of the next line down. This experiment was designed to mimic as closely as possible the type of eye movements required when reading. This condition is referred to as scanning right-left discrimination (SRLD)

3.3 - Results

3.3.1- Random Left-Right Discrimination Task

The children were split into two groups on the basis of the Dunlop Test. Those with stable responses formed one group while the children with unstable responses formed the other (see General Methods for description of Dunlop Test categorisation). This classification produced a group of 83 children with stable responses on the Dunlop Test and 79 with unstable responses. The total number of trials recorded for children with stable reference was 2044 while 1789 trials were recorded from children with unstable responses on the Dunlop Test.

Figure 3.4 shows the percentage errors made by all children with stable Dunlop Test responses compared with those with unstable responses. The percentage error was calculated by dividing the number of incorrect responses by the total number of trials. The percentage error rate should lie between 0% (all correct) and 50% (the expected error rate produced by random guessing). There was a significant difference between the two groups with both percentage errors lying between the floor and ceiling limits. The children with stable responses on the Dunlop Test showed an average error rate of 21.8% while the children with unstable responses scored 29.7% ($\chi^2 = 31.04$; DOF = 1; $p < 0.001$).

There are clear developmental trends in the acquisition of stable Dunlop Test responses and in gaining stable vergence eye movements

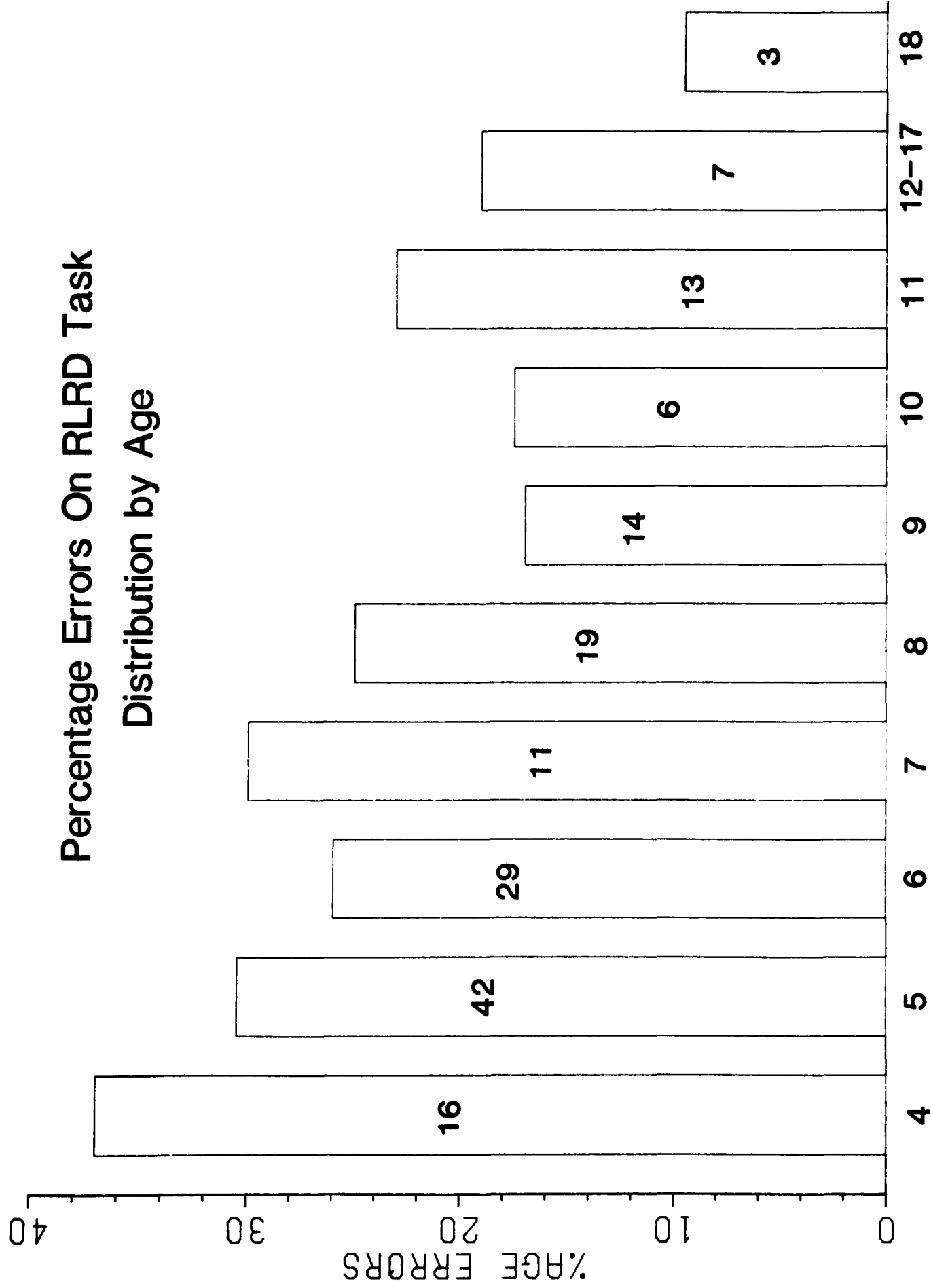


Figure 3.5 - Bar chart showing the percentage error rate on the RLRD task for children of increasing age. The chart represents the developmental trend for increasing accuracy of spatial localisation with increasing age. The number of children tested at each age level is shown.

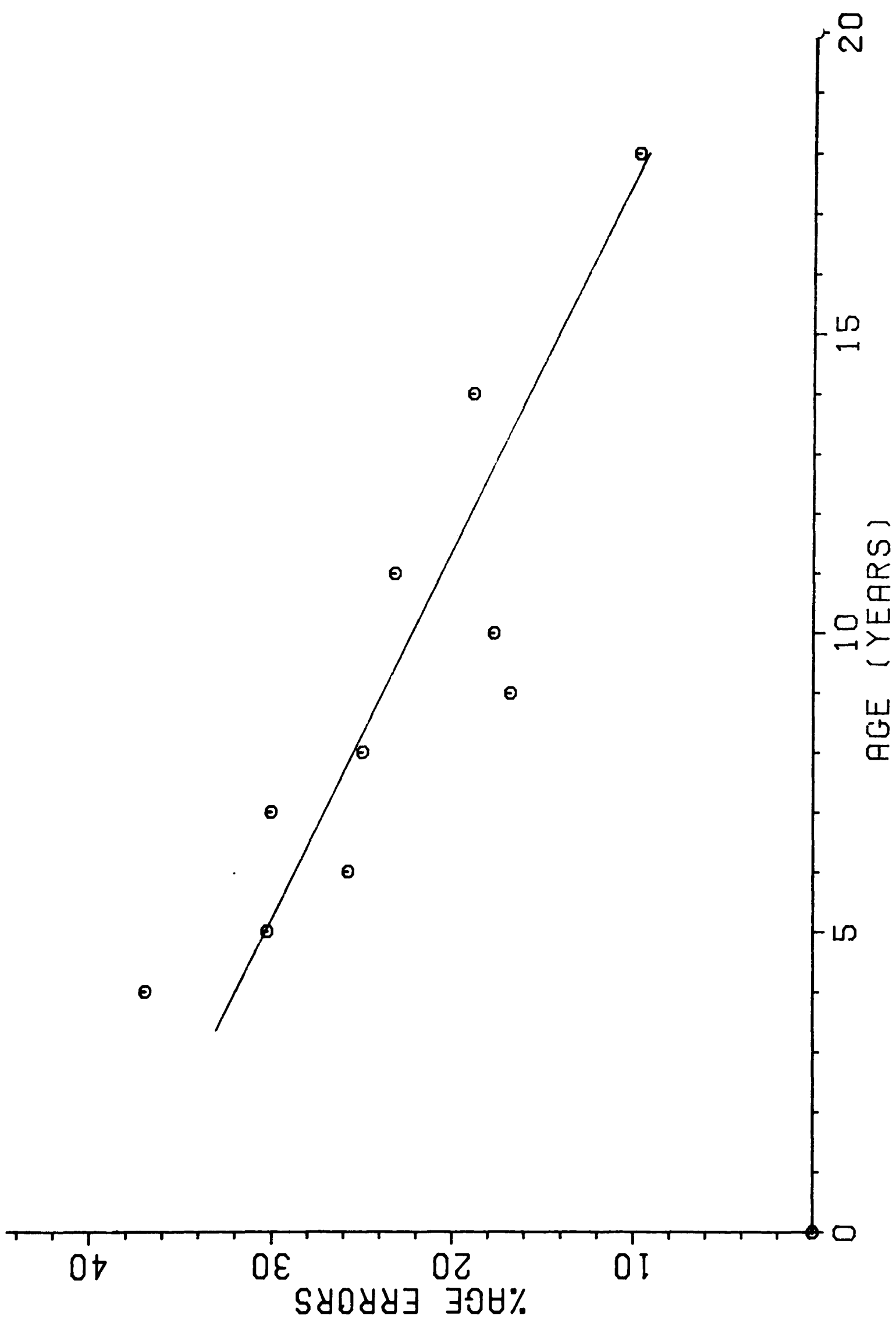


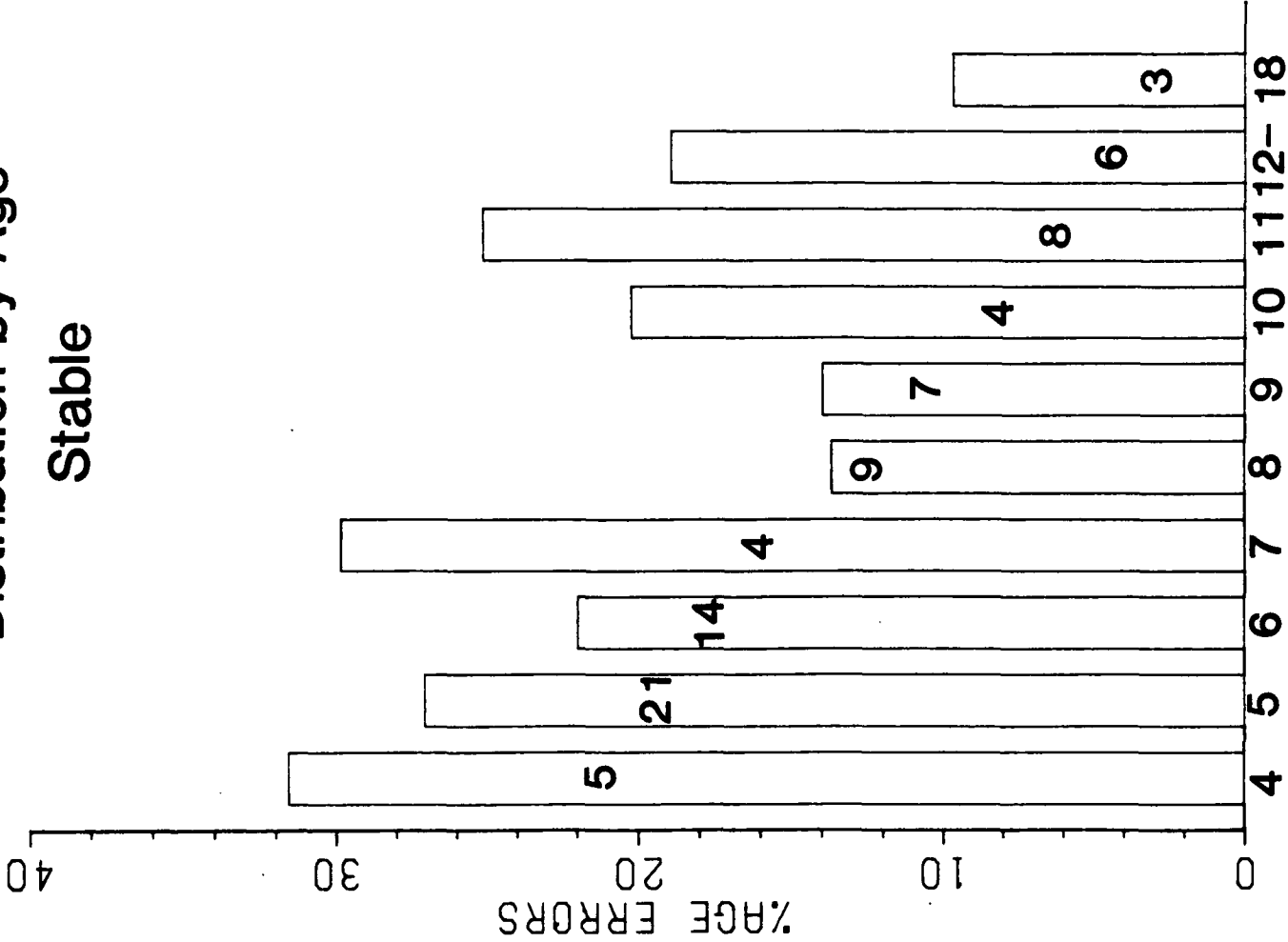
Figure 3.5a - Regression of percentage error rate in the RLRD task against age. The regression line was calculated using the data displayed in Figure 3.5.

(see chapter 4). Since it is postulated that the accuracy of spatial discrimination is linked to the stability of Dunlop Test responses and eye movements, the children's performance (stable and unstable combined) were organised into age groups in order to see if the same developmental trend was evident. Figure 3.5 shows the results of this analysis. Among the 4 year olds, whether stable or unstable the average percentage error was 36.9%. This decreased to 9.7% in subjects over 18 years. The percentage error was regressed against age. This produced the regression line shown in Figure 3.5a. The change in age explained 75% of the variance in percentage error. Hence there is a strong correlation between increasing spatial accuracy in this task and increasing age.

The hypothesis that accuracy of spatial discrimination is linked to the accuracy of vergence control predicts that the age distribution of errors for the stable versus the unstable groups should be different. Specifically, children with stable Dunlop Test results should make fewer errors at all ages, and should show the greatest improvement with age. Table 3.1 shows the distribution of errors by age for children with stable compared with those with unstable Dunlop Test responses. A histogram of this distribution is plotted in Figure 3.6.

There was a clear trend for the children with stable Dunlop Test responses to make fewer errors than those with unstable Dunlop Test responses up to the age of 10. At this point the trend reverses. This was a surprising result. However the number of children in each of the age groups over 9 years was small, especially for the unstable condition.

Percentage Errors On RLRD Task
Distribution by Age
Stable



Percentage Errors On RLRD Task
Distribution by Age
Unstable

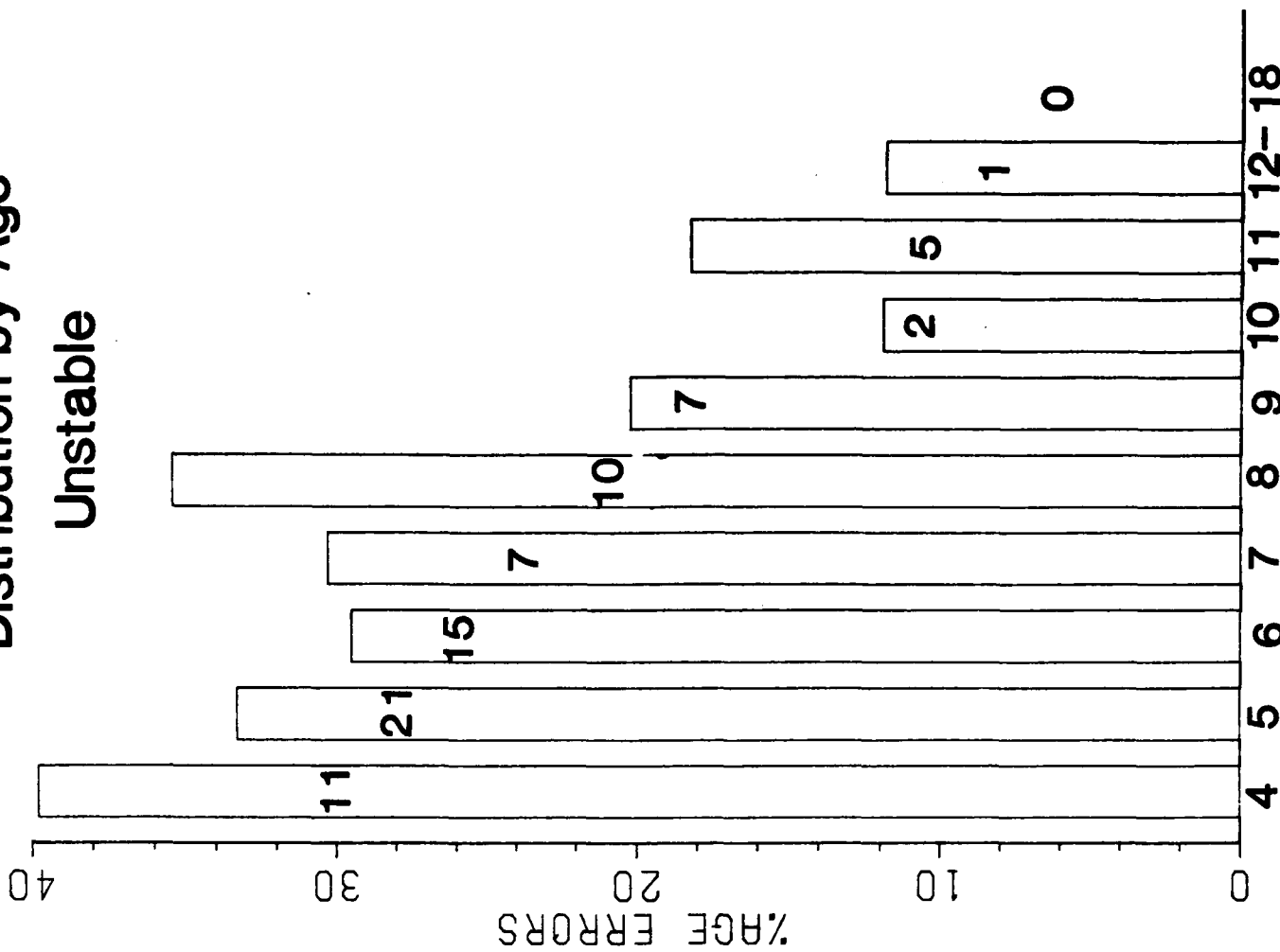
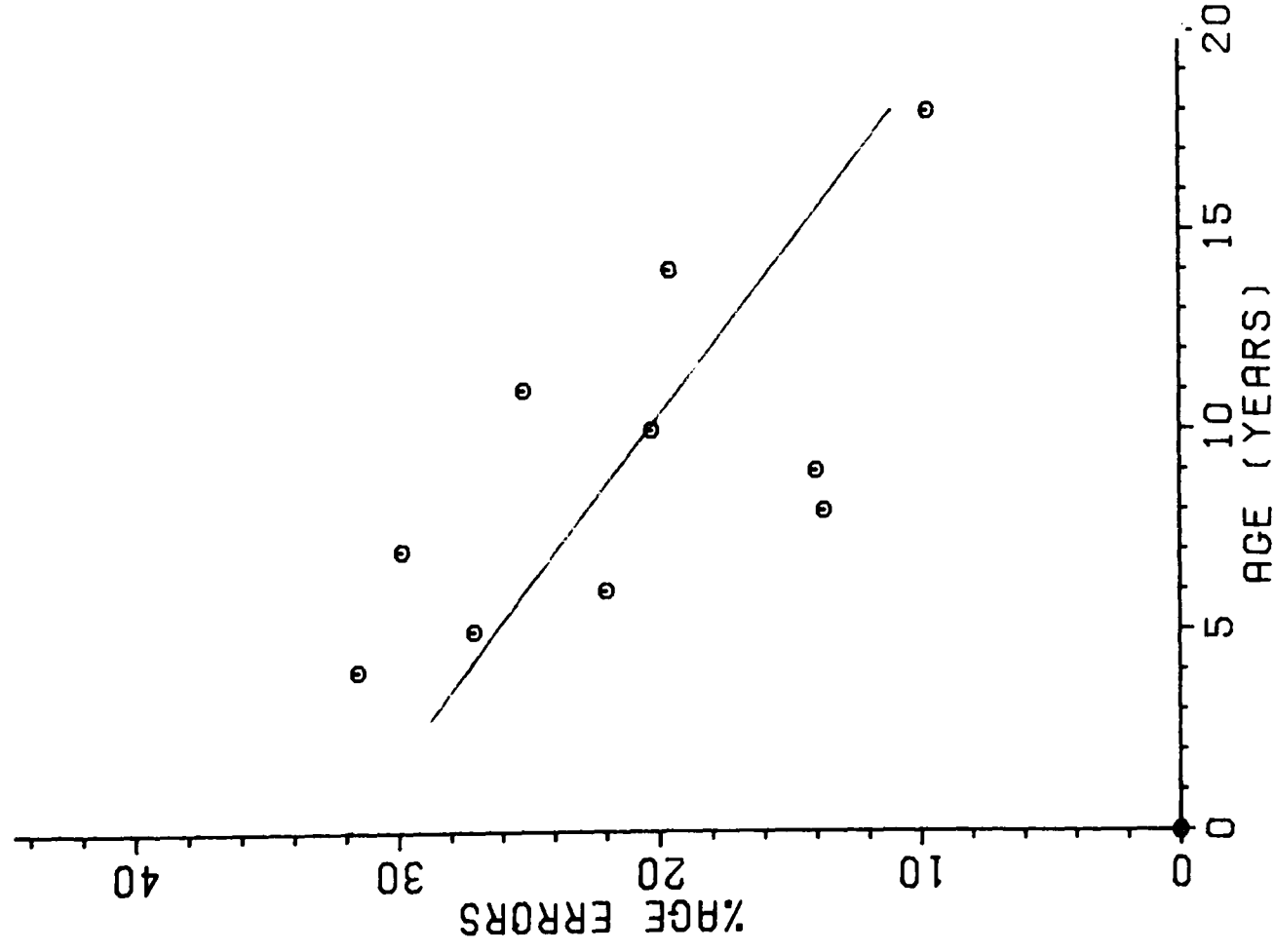


Figure 3.6 - Bar charts comparing the developmental curves for spatial localisation tested using the RLRD task in children with stable Dunlop Test responses compared with those with unstable responses. The number of children tested at each age level is shown.

Age (Years)	Stable	Unstable
4	36/114	84/210
	31.6%	39.8%
5	126/464	158/474
	27.1%	33.3%
6	73/332	104/353
	22.0%	29.5%
7	32/107	46/152
	29.9%	30.3%
8	30/219	84/237
	13.7%	35.4%
9	26/185	30/148
	14.0%	20.2%
10	27/133	7/59
	20.3%	11.9%
11	55/218	16/88
	25.2%	18.2%
12-17	29/148	2/17
	19.6%	11.8%
18 ⁺	7/72	-
	9.7%	-

Table 3.1 - RLRD task - Distribution of errors by age for stable versus unstable Dunlop Test responses.

Stable



Unstable

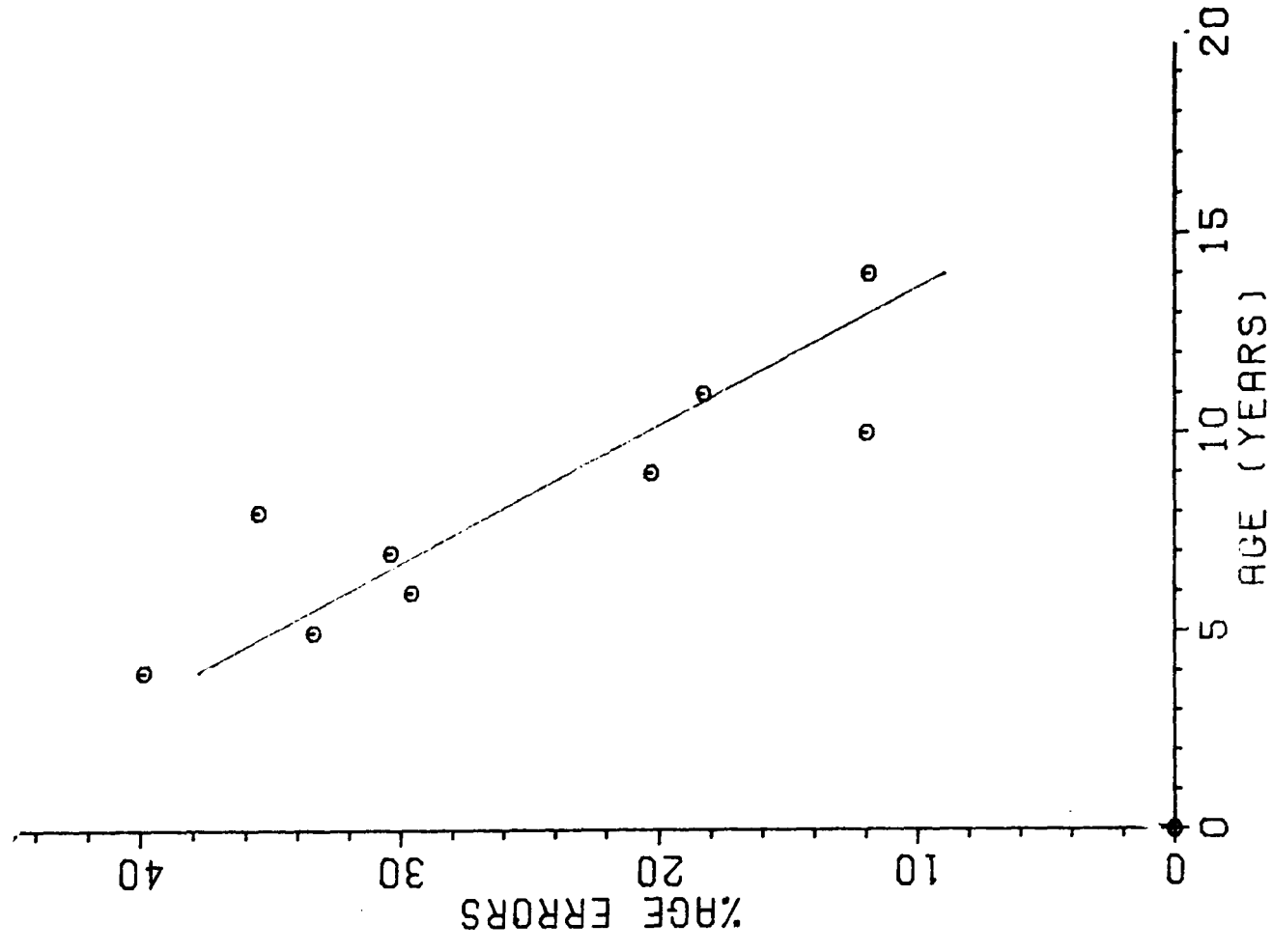


Figure 3.6a - Regression of percentage error rate in the RLRD task against age for children with stable compared with those with unstable Dunlop Test responses. The regression lines were calculated using the data displayed in Figure 3.6 and Table 3.1.

Regression coefficients were calculated for the change in percentage error with age in both the stable and unstable groups. The slope of the regression line calculated for the unstable group on the RLRD task was higher than for the stable group. This is due to the relatively poor performance of the younger unstable children on this task.

It has been suggested that females are poorer on tests of visuospatial perception than males (McGee, 1979). This hypothesis was therefore investigated by comparing 52 females with 110 males. It is known that the number of male dyslexics exceeds the number of female dyslexics by a ratio of about 5:1. The ratio of males to females in this sample is not so high since it contained many normal children. The total number of trials for males was 2634 and for females was 1199. Figure 3.7 shows the results of comparing their errors. The females averaged a percentage error rate of 28.2% while the males averaged 24.2%. This difference was statistically significant ($\chi^2 = 6.70$; DOF = 1; $p < 0.01$).

	Stable	Unstable	Total
	-----	-----	-----
	134/580	202/619	336/1199
Females	23.4%	32.6%	28.2%
	n = 25	n = 27	n = 52
	-----	-----	-----
	310/1464	329/1170	639/2634
Males	21.2%	28.1%	24.2%
	n = 58	n = 52	n = 110
	-----	-----	-----
	444/2044	531/1789	975/3833
Total	21.8%	29.7%	25.5%
	n = 83	n = 79	n = 162
	-----	-----	-----

Table 3.2 - Errors in RLRD task categorised by sex and Dunlop Test results.

Percentage errors on RLRD Task Females vs. Males

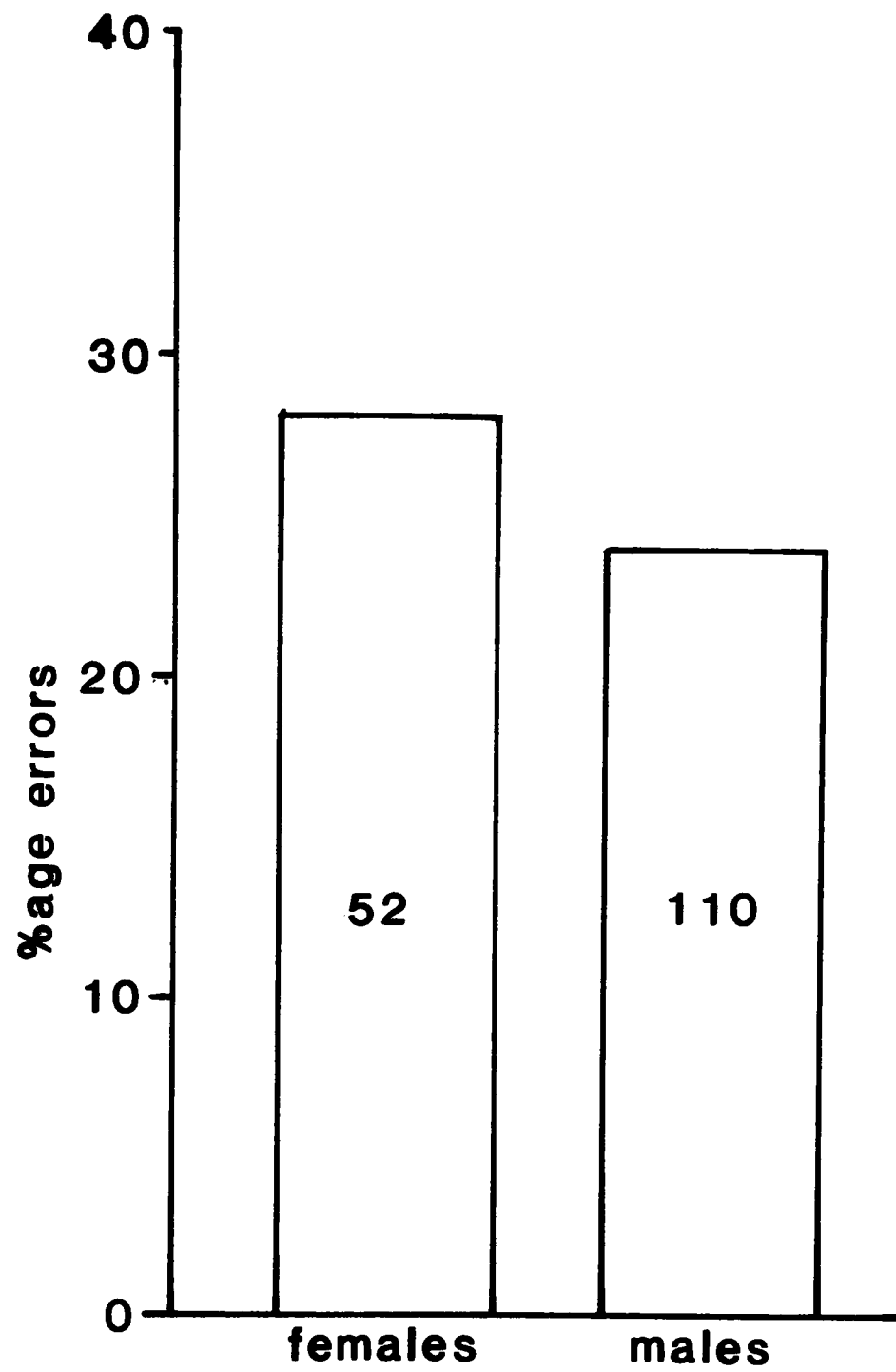


Figure 3.7 - Bar chart showing the percentage error rate of 53 females compared with 110 males on the RLRD task.

Thus significant differences were found between the males and the females and between the children with stable compared with unstable Dunlop Test responses. Therefore, the possibility of interactions between these two conditions was investigated. Table 3.2 shows a breakdown of these results.

There was a significant difference found in both males and females when the stable versus unstable groups were compared:

Males: Stable vs. Unstable - $\chi^2 = 17.07$, DOF = 1, $p < 0.001$

Females: Stable vs. Unstable - $\chi^2 = 10.31$, DOF = 1, $p < 0.01$

The percentage errors made by males with stable Dunlop Test responses were then compared with the errors made by similar females. This comparison was also made for children with unstable Dunlop Test responses: unstable females were found to make significantly more errors than stable females. However, the same comparison did not reach statistical significance for males:

Stable: Males vs. Females - $\chi^2 = 1.26$, DOF = 1, $p < 0.50$

Unstable: Males vs. Females - $\chi^2 = 3.95$, DOF = 1, $p < 0.05$

This shows that unstable males and unstable females were dominating the overall results by making more errors than their stable counterparts. However, the unstable females made most errors of all.

This experiment also gave the opportunity to assess the different contributions made by the two hemispheres to the processing required in this visuospatial discrimination task, because it was possible to look at the errors made in each visual field. The anatomy of the visual pathways is organised so that the information from each half of the visual field arrives first in the contralateral hemisphere regardless of which eye sees the stimulus (see Figure 3.1). In the present task, subjects were told to fixate a priming spot. This

Percentage Errors On RLRD Task

Percentage Errors On RLRD Task

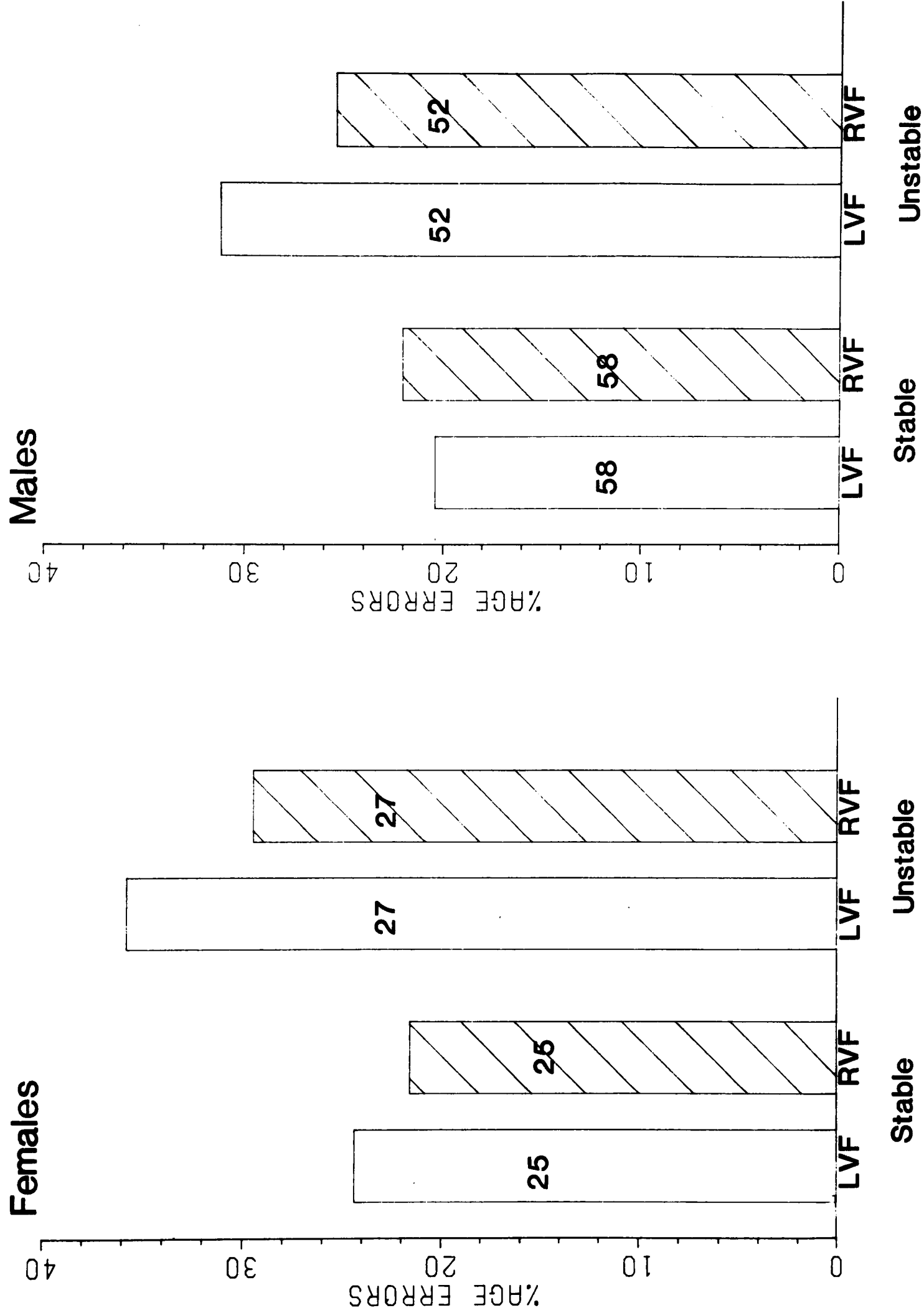


Figure 3.8 - Bar charts showing the percentage error rate on the RLRD task for children with stable compared with unstable Dunlop Test responses. The results have been divided by visual field and sex. The number of children tested in each condition is shown.

ensured that the test spot appearing subsequently would be processed first by one or other hemisphere depending on which side of the priming spot it appeared. The results were therefore grouped according to the visual field in which the test spot appeared: left visual field-right hemisphere (LVF-RH) errors and RVF-LH errors.

Figure 3.8 shows the results of analysis by visual field. Taking all subjects together, there was a slight visual field advantage for the RVF-LH condition (RVF-LH = 24.2%, $n = 162$, total no. of trials = 1908; LVF-RH = 26.6%, $n = 162$, total no. of trials = 1925). This, however, did not reach statistical significance ($\chi^2 = 2.99$, DOF = 1, $p < 0.10$). Thus, overall, there were no hemispheric differences in the processing of this task.

However, it was possible that children with stable vergence control might process the stimuli differently from those with unstable control measured using the Dunlop Test. Moreover, there is fairly strong evidence that males and females differ in the degree of specialisation of the two hemispheres (Springer and Deutsch, 1985). In view of this, the results were reanalysed by sex and by stability of Dunlop Test responses with respect to left-right visual field differences. Table 3.3 summarises these results.

Comparison of RVF-LH with LVF-RH errors in males and females separately showed no significant differences in either sex (Males - $\chi^2 = 0.82$, DOF = 1, $p < 0.50$; Females - $\chi^2 = 2.77$, DOF = 1, $p < 0.10$). The trend for females to make more errors in the LVF was stronger, however, since females made many more errors than males in the LVF-RH condition.

	RVF	LVF	S	U	M	F	Total
RVF			217/ 991	245/ 917	311/ 1323	151/ 585	462/ 1908
			21.9%	26.7%	23.5%	25.8%	24.2%
			n = 83	n = 79	n = 110	n = 52	n = 162
LVF			227/ 1053	286/ 872	328/ 1311	185/ 614	513/ 1925
			21.5%	32.8%	25.0%	30.1%	26.6%
			n = 83	n = 79	n = 110	n = 52	n = 162
S	217/ 991	227/ 1053			310/ 1464	134/ 580	444/ 2044
	21.9%	21.5%			21.2%	23.4%	21.7%
	n = 83	n = 83			n = 58	n = 25	n = 83
U	245/ 917	286/ 872			329/ 1170	202/ 619	531/ 1789
	26.7%	32.8%			28.1%	32.6%	29.7%
	n = 79	n = 79			n = 52	n = 27	n = 79
M	311/ 1323	328/ 1311	310/ 1464	329/ 1170			639/ 2634
	23.5%	25.0%	21.2%	28.1%			24.2%
	n = 110	n = 110	n = 58	n = 52			n = 110
F	151/ 585	185/ 614	134/ 580	202/ 619			336/ 1199
	25.8%	30.1%	23.4%	32.6%			28.2%
	n = 52	n = 52	n = 25	n = 27			n = 52
Total	462/ 1908	513/ 1925	444/ 2044	531/ 1789	639/ 2634	336/ 1199	975/ 3833
	24.2%	26.6%	21.7%	29.7%	24.2%	28.2%	25.5%
	n = 162	n = 162	n = 83	n = 79	n = 110	n = 52	n = 162

Table 3.3 - Distribution of errors in the left and right visual fields versus sex and stability of Dunlop Test responses in the RLRD task. S - stable Dunlop Test responses; U - unstable Dunlop Test responses; M - males; F - females.

This trend was confirmed by comparing males and females in the LVF-RH condition alone. The difference was significant at $p < 0.02$ ($\chi^2 = 5.59$, $\text{DOF} = 1$, $p < 0.02$). This confirms that females made many more errors in the LVF-RH condition than the males. There was no statistical significance between males and females for the RVF-LH errors however.

Comparing RVF-LH and LVF-RH errors in subjects with stable Dunlop Test responses, and also in those with unstable responses, a significant difference favouring the RVF-LH was found for those with unstable responses but not for those with stable responses (Stable - $\chi^2 = 0.03$, $\text{DOF} = 1$, $p > 0.50$; Unstable - $\chi^2 = 7.92$, $\text{DOF} = 1$, $p < 0.01$). This difference arose because children with unstable Dunlop Test responses made a far greater number of errors in the LVF-RH.

This time both the RVF-LH and the LVF-RH conditions show statistical significance. When stable and unstable response groups were compared for LVF or RVF errors, on the other hand, unstable children were significantly worse in both visual fields than those with stable vergence control (RVF-LH - $\chi^2 = 6.03$, $\text{DOF} = 1$, $p < 0.02$; LVF-RH - $\chi^2 = 30.83$, $\text{DOF} = 1$, $p < 0.001$). This was due to the greater number of errors made by children with unstable Dunlop Test responses in all conditions. However, the significance of the difference between stable and unstable responses was much greater in the LVF-RH condition because of the particularly high error rate of children with unstable Dunlop Test responses in this field.

This analysis suggests, therefore, that females and children with unstable responses on the Dunlop Test are more likely to make errors in the LVF-RH condition. Could this have been a result of females with unstable responses making the largest contribution to the error rate in the LVF-RH condition?

Tables 3.4 a and b show the distribution of average error rate between the LVF-RH and RVF-LH for stable and unstable males and females.

Table 3.4a

	<u>Females</u>	
	S	U
	59/273	92/312
R	21.6%	29.5%
	n = 25	n = 27
	75/307	110/307
L	24.4%	35.8%
	n = 25	n = 27

Table 3.4b

	<u>Males</u>	
	S	U
	158/718	153/605
R	22.0%	25.3%
	n = 58	n = 52
	152/746	176/565
L	20.4%	31.1%
	n = 58	n = 52

Table 3.4a and b - distribution of LVF-RH and RVF-LH conditions for stable and unstable Dunlop Test responses in males and females in the RLRD task. S - stable Dunlop Test responses, U - unstable Dunlop Test responses, R - RVF-LH condition, L - LVF-RH condition.

Comparison of the LVF-RH errors in unstable females versus unstable males showed that the females did score a higher error rate in this condition. However, the difference did not reach statistical significance ($\chi^2 = 1.98$, DOF = 1, $p < 0.50$). Unstable females also make more errors in the LVF-RH condition than in the RVF-LH condition. Again, however, this difference was not statistically significant ($\chi^2 = 2.83$, DOF = 1, $p < 0.10$). There was a statistically significant difference between the females with stable Dunlop Test responses versus those with unstable responses in the LVF-RH condition ($\chi^2 = 9.48$, DOF = 1, $p < 0.01$). This suggests that, although the unstable females have the highest average error rate in the LVF-RH condition, theirs was not the main contribution being made to the greater error rate in this condition.

This was confirmed by considering the error rate of males in the LVF-RH condition. Here it can be seen that males with unstable responses on the Dunlop Test made significantly more errors in the LVF than their stable counterparts ($\chi^2 = 19.89$, DOF = 1, $p < 0.001$). In fact, the significantly different error rate found between stable and unstable males can be attributed almost exclusively to differences in the LVF-RH since there was no difference between stable and unstable males in the RVF ($\chi^2 = 1.97$, DOF = 1, $p < 0.50$). This is supported by the significant difference that is found between the LVF-RH and the RVF-LH condition in unstable males ($\chi^2 = 4.96$, DOF = 1, $p < 0.05$), with the unstable males showing the highest error rate.

To summarise these results, female subjects with unstable responses in the Dunlop Test made more errors in both visual fields. There was a trend towards a higher error rate in the LVF-RH condition in females which did not reach significance. In males, the subjects with unstable responses on the Dunlop Test make more errors but in this case only the LVF-RH error rate in unstable males was significantly higher than that in stable males.

3.3.2 - Scanning Left-Right Discrimination Task

As in the RLRD task, for this task subjects were first classified on the basis of their Dunlop Test responses. This resulted in a group of 89 children with stable responses on the Dunlop Test and a group of 83 children with unstable responses. The total number of trials analysed was 2088 for the stable children and 1784 for the unstable children.

Figure 3.9 shows the percentage errors made by all children with stable compared with those with unstable Dunlop Test responses. The average error rate for children with stable responses was 21.8% while

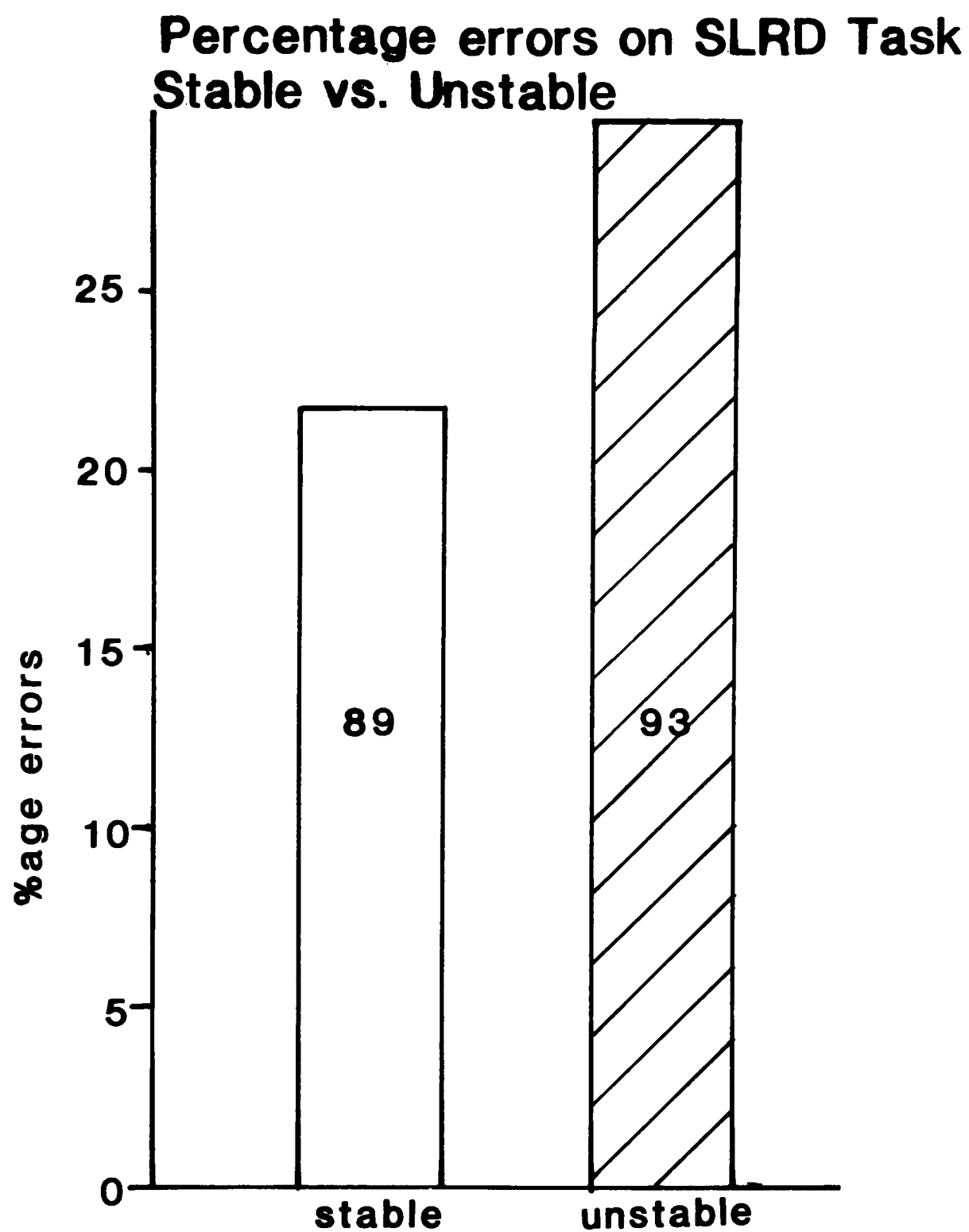


Figure 3.9 - Bar chart showing the percentage errors made by 89 children with stable Dunlop Test responses compared with those of 83 children with unstable responses on the SLRD task.

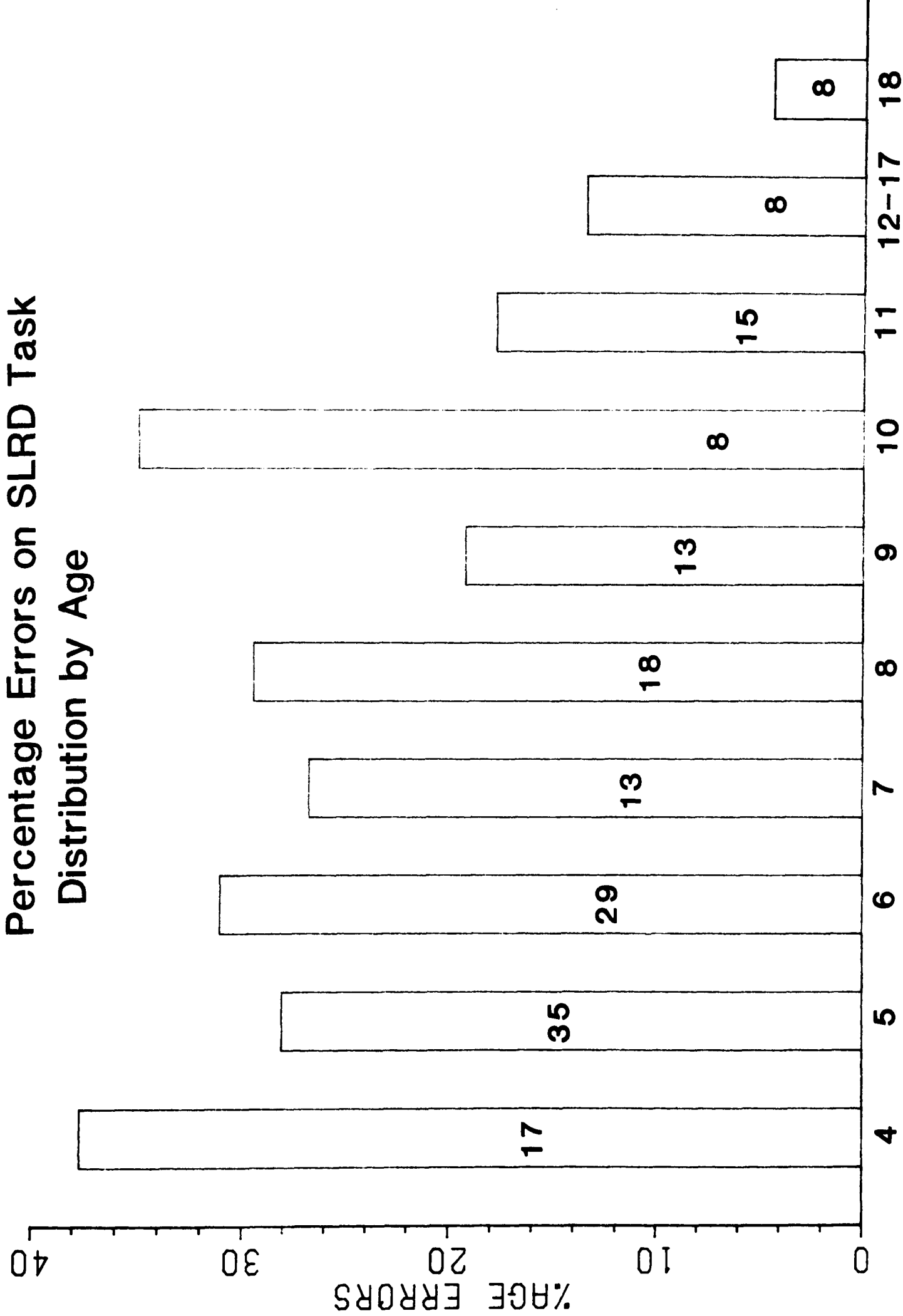


Figure 3.10 - Bar chart showing the percentage error rate on the SLRD task for children of increasing age. The chart represents the developmental trend for increasing accuracy of spatial localisation with increasing age. The number of children tested at each age level is shown.

those with unstable responses showed an average error rate of 29.9%. There was a significant difference between these two figures ($\chi^2 = 33.97$, DOF = 1, $p < 0.001$).

The developmental trend in the error rate for the SLRD task was also investigated. Figure 3.10 shows that the average error rate fell each year. At 4 years the error rate was 37.7% while adults showed an average error rate of only 4.4%. Figure 3.10a shows the regression line for this trend. The change in age explains 75% of the variance in percentage error. Hence there is a strong correlation between increasing accuracy on this spatial localisation task and increasing age.

The age distribution of errors made in the SLRD task by stable compared with unstable Dunlop Test responses is shown in Table 3.5 and the results are plotted in Figure 3.11. As expected, the developmental trend for increasing accuracy in the spatial discrimination task was stronger for children with stable Dunlop Test responses than in those with unstable responses. At most age levels, the children with unstable Dunlop Test responses made more errors than their stable counterparts. There are only two age groups for which this was not true. These were the children of 4 and of 10 years old.

A possible explanation was suggested in section 3.3.1 for why this reversal might occur. This was that the numbers in the groups were so small that no significant differences could be found.

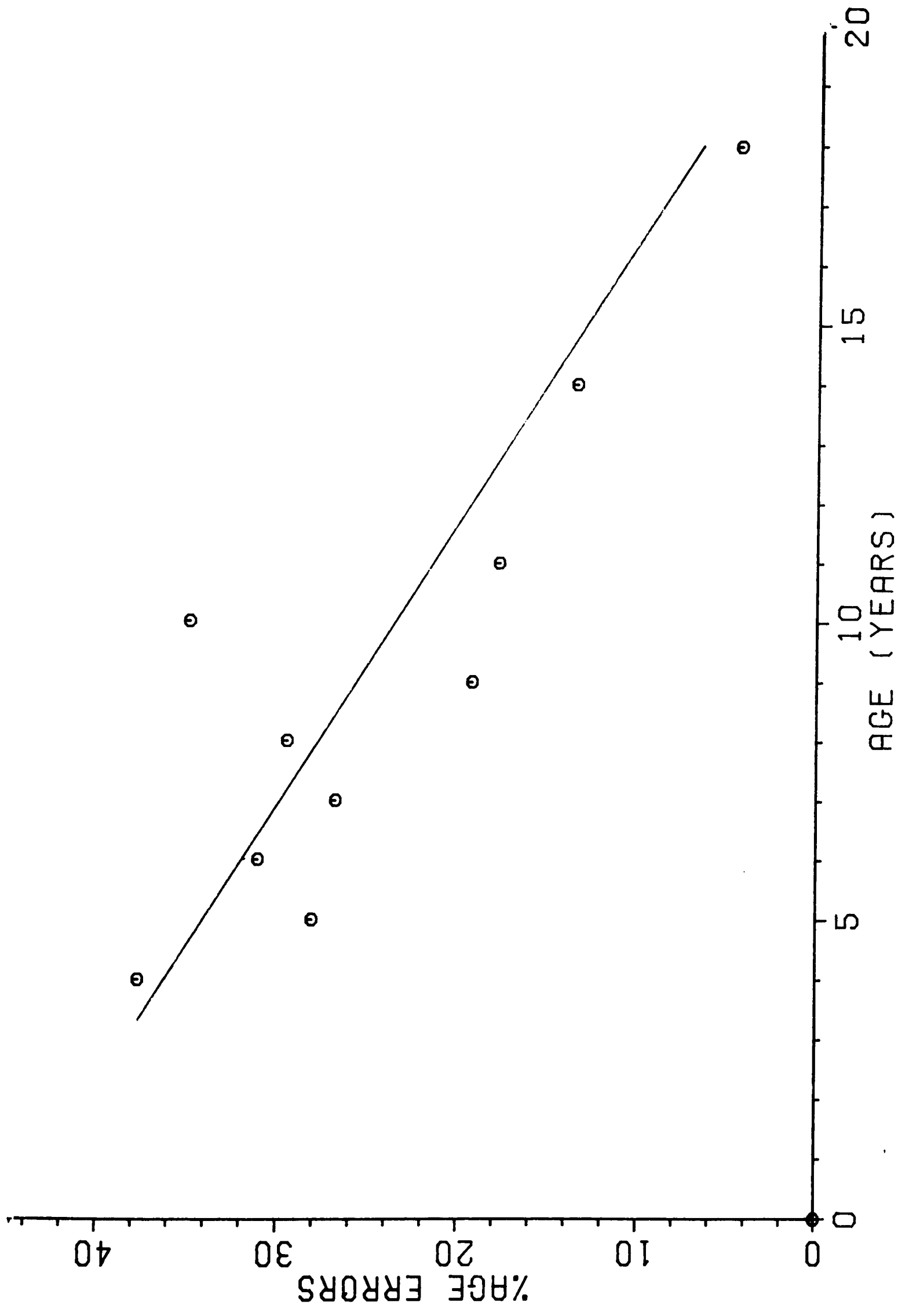
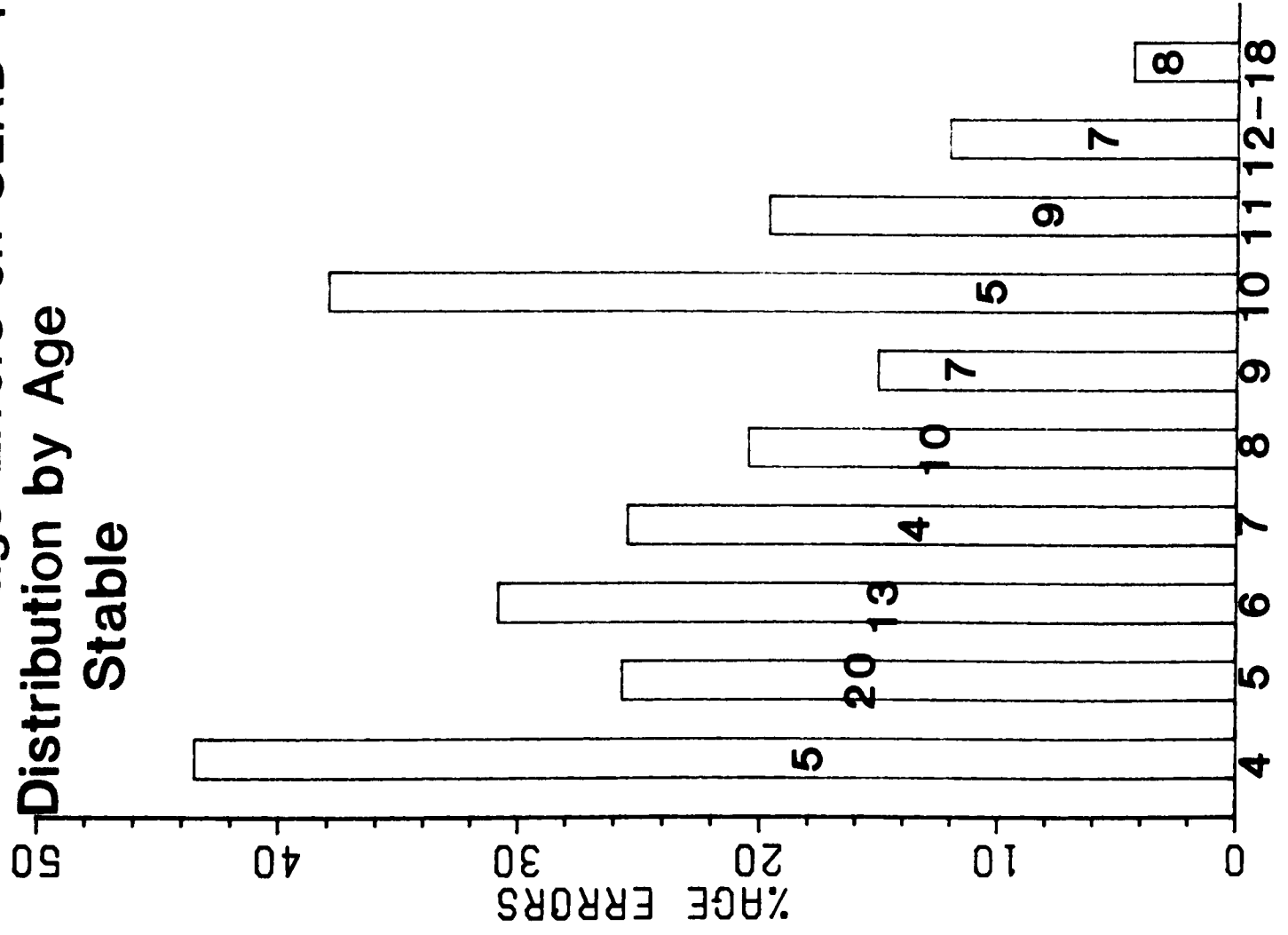


Figure 3.10a - Regression of percentage error rate in the SLRD task against age. The regression line was calculated using the data displayed in Figure 3.10.

Age (Years)	Stable	Unstable
4	40/92	71/202
	43.5%	35.1%
5	103/401	91/289
	25.7%	31.5%
6	85/275	116/371
	30.9%	31.3%
7	23/90	56/205
	25.5%	27.3%
8	53/258	84/207
	20.5%	40.6%
9	25/166	32/131
	15.1%	24.4%
10	48/126	20/69
	38.1%	28.9%
11	49/248	21/147
	19.7%	14.3%
12-17	21/174	5/20
	12.1%	25.0%
18 ⁺	11/251	-
	4.4%	-

Table 3.5 - SLRD task - Distribution by age for stable versus unstable Dunlop Test responses.

Percentage Errors on SLRD Task
Distribution by Age
Stable



Percentage Errors on SLRD Task
Distribution by Age
Unstable

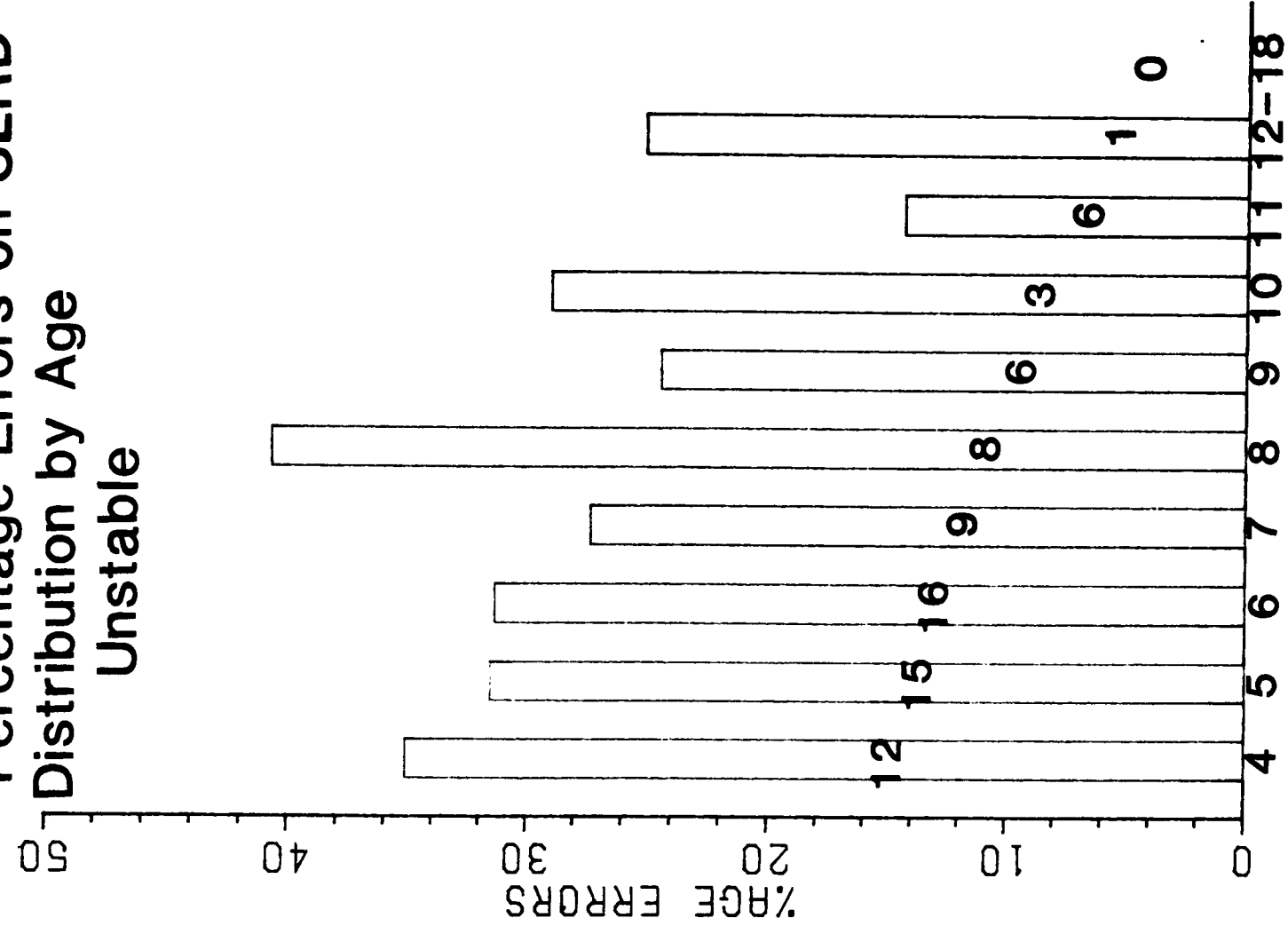


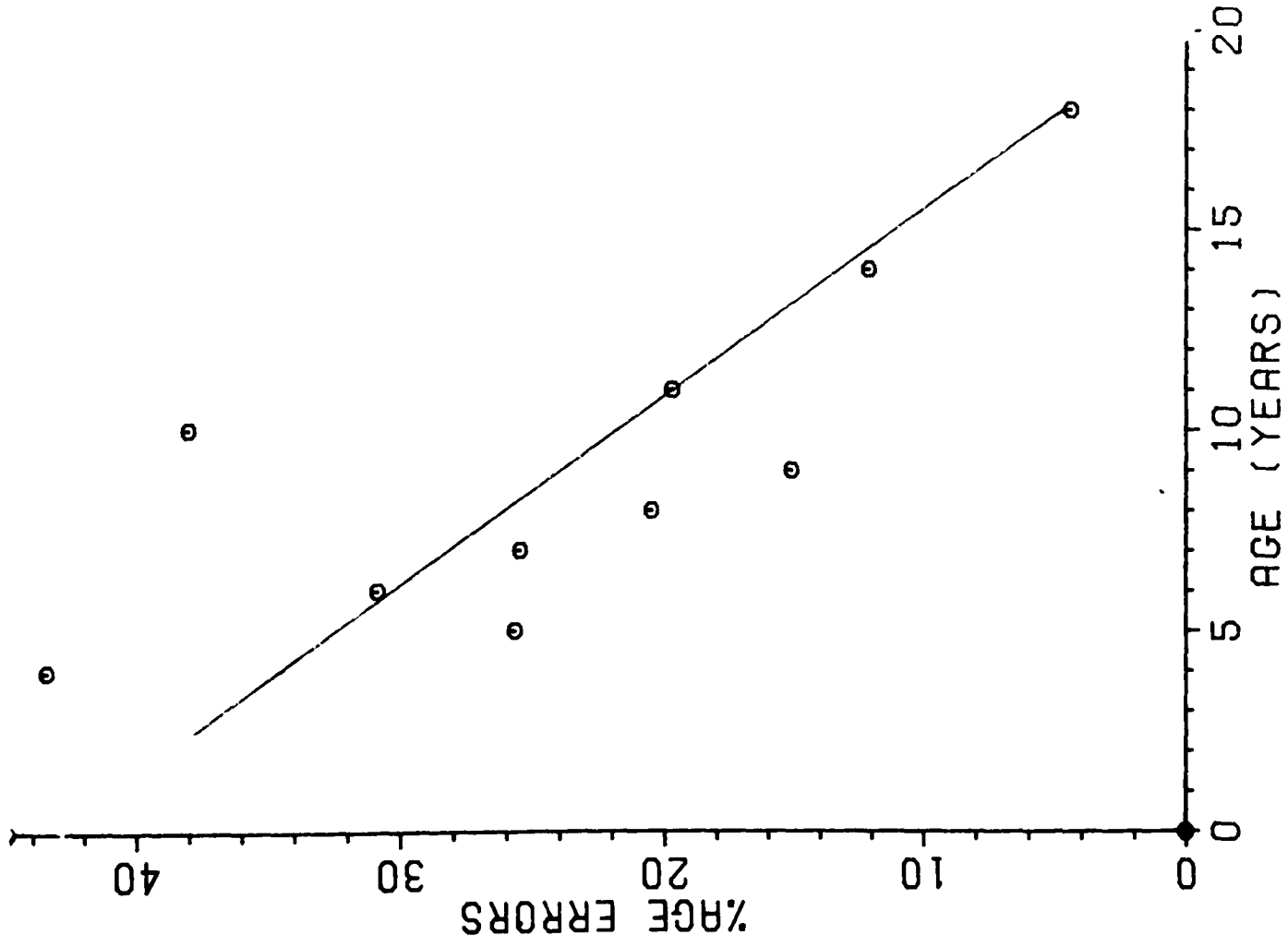
Figure 3.11 - Bar charts comparing the developmental curves for spatial localisation tested using the SLRD task in children with stable Dunlop Test responses compared with those with unstable responses. The number of children tested at each age level is shown.

The regression coefficients of age against error rate for those with stable and unstable Dunlop Test responses were calculated. The slope of the developmental trend for the stable children has a greater slope than that for the unstable children. Since the younger children make approximately equal errors, whether stable or unstable, on this test, this increased slope must be due to the more accurate performance of older children with stable Dunlop Test responses. It would be expected that the children with stable responses might continue to improve their accuracy of spatial localisation with time while those with unstable spatial localisation would be unable to improve their abilities. The trends found for the experiment support this hypothesis.

The developmental trends found for stable compared with unstable children on this scanning task were different from those found for the random spatial localisation task. In it, the greater slope was found for the unstable children. This was found to be the result of the poor performance of the younger children on this task. It seems that the younger children with unstable responses in the Dunlop Test find the random localisation task particularly difficult, while older children with stable Dunlop Test responses find the scanning task particularly easy. This gives a differential bias to the developmental trends for each task.

The subjects were then grouped by sex. There were 58 females and 114 males. Females performed a total of 1315 trials while the males performed 2557 trials. Figure 3.12 shows the resulting distribution of errors. The females had an average error rate of 26.5% while the males showed 25.1%. This difference did not quite reach statistical significance ($\chi^2 = 0.99$, DOF = 1, $p < 0.50$).

Stable



Unstable

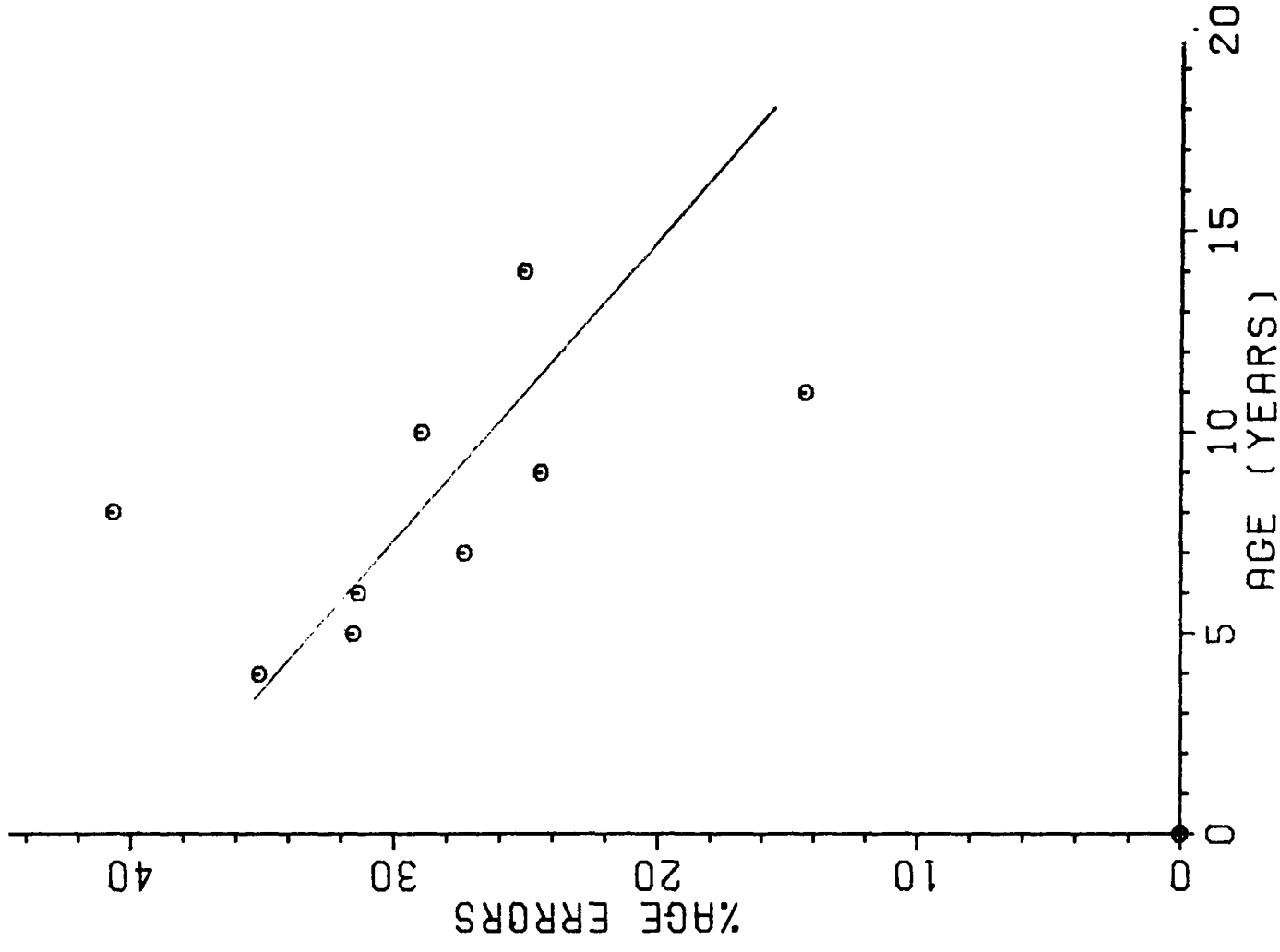


Figure 3.11a - Regressions of percentage error rate in the SLRD task against age for children with stable compared with those with unstable Dunlop Test responses. The regression lines were calculated using the data displayed in Figure 3.6 and Table 3.5.

Percentage errors on SLRD Task
Females vs. Males

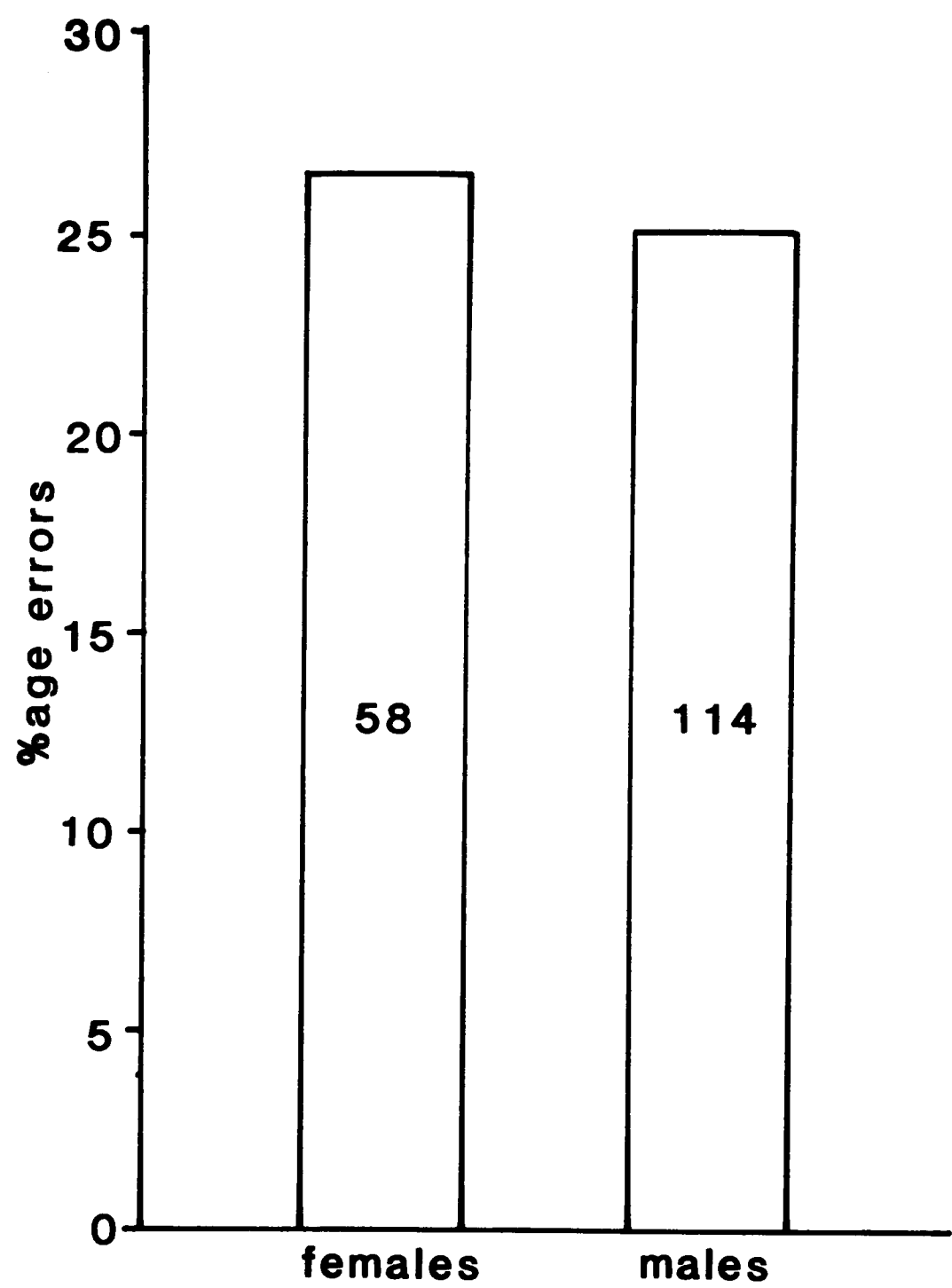


Figure 3.12 - Bar chart showing the percentage error rate of 58 females compared with 114 males on the SLRD task.

The results were then analysed by sex and Dunlop Test responses to see whether the sex difference found in the RLRD task could also be shown in this task. Table 3.6 shows these results.

	Stable	Unstable	Total
	142/655	207/660	349/1315
Females	21.8%	31.4%	26.5%
	n = 28	n = 30	n = 58
	313/1433	328/1124	641/2557
Males	21.8%	29.2%	25.1%
	n = 61	n = 53	n = 114
	445/2088	535/1784	990/3872
Total	21.8%	29.9%	25.6%
	n = 89	n = 83	n = 172

Table 3.6 - Results of SLRD task categorised by sex and Dunlop Test results.

Thus there was a significant difference between the stable and unstable groups for both males and females:

Males - Stable vs. Unstable - $\chi^2 = 18.06$, DOF = 1, $p < 0.001$

Females - Stable vs. Unstable - $\chi^2 = 15.81$, DOF = 1, $p < 0.001$.

Within the stable and the unstable groups however there was no statistically significant difference between the error rates scored by males compared with females:

Stable - Males vs. Females - $\chi^2 = 0.007$, DOF = 1, $p > 0.5$

Unstable - Males vs. Females - $\chi^2 = 0.94$, DOF = 1, $p < 0.5$.

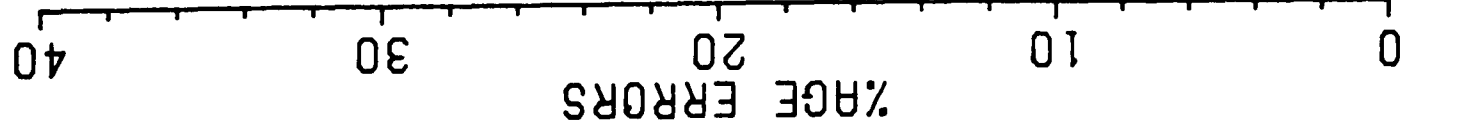
Hence, it was probably lack of stable Dunlop Test responses which carried the high error rate rather than differences between males and females. Both sexes contributed to the difference in errors.

	RVF	LVF	S	U	M	F	Total
RVF			207/ 1002	255/ 851	306/ 1254	156/ 599	462/ 1853
			20.6%	29.9%	24.4%	26.0%	24.9%
			n = 89	n = 83	n = 114	n = 58	n = 172
LVF			248/ 1086	280/ 933	335/ 1303	193/ 716	528/ 2019
			22.8%	30.0%	25.7%	26.9%	26.1%
			n = 83	n = 79	n = 110	n = 52	n = 162
S	207/ 1002	248/ 1086			313/ 1433	142/ 655	455/ 2088
	20.6%	22.8%			21.8%	21.8%	21.8%
	n = 89	n = 89			n = 61	n = 28	n = 89
U	255/ 851	280/ 933			328/ 1124	207/ 660	535/ 1784
	29.9%	30.0%			29.2%	31.4%	29.9%
	n = 83	n = 83			n = 53	n = 30	n = 83
M	306/ 1254	325/ 1303	313/ 1433	328/ 1124			641/ 2557
	24.4%	25.7%	21.8%	29.2%			25.1%
	n = 110	n = 110	n = 58	n = 52			n = 110
F	156/ 599	193/ 716	142/ 655	207/ 660			349/ 1315
	26.0%	26.9%	21.8%	31.4%			26.5%
	n = 58	n = 58	n = 28	n = 30			n = 58
Total	462/ 1853	528/ 2019	455/ 2088	535/ 1784	641/ 2557	349/ 1315	990/ 3872
	24.9%	26.1%	21.8%	29.9%	25.1%	26.5%	25.6%/
	n = 172	n = 172	n = 89	n = 83	n = 114	n = 58	n = 172

Table 3.7 - Distribution of errors in the left and right visual fields versus sex and stability of Dunlop Test responses in the SLRD task. S - stable Dunlop Test responses; U - unstable Dunlop Test responses; M - males; F - females.

Percentage Errors on SLRD Task

Females



Percentage Errors on SLRD Task

Males

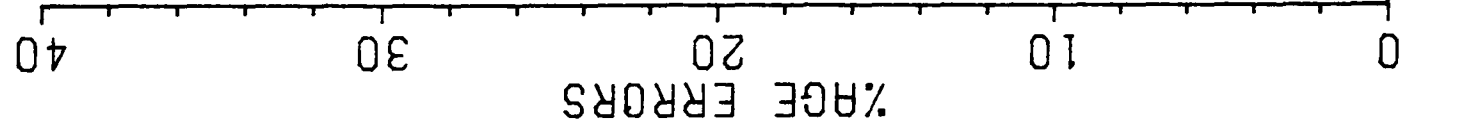


Figure 3.13 ~ Bar charts showing the percentage error rate on the SLRD task for children with stable compared with unstable Dunlop Test responses. The results have been divided by visual field and sex. The number of children tested in each condition is shown.

The results were then analysed with respect to the two hemifields. Figure 3.13 shows the percentage error rates for each visual field. There was a slightly higher error rate in the LVF-RH (LVF-RH: 26.1%, n = 174, total no. of trials = 1853, RVF-LH: 24.9%, n = 174, total no. of trials = 2019). This difference did not reach statistical significance ($\chi^2 = 0.75$, DOF = 1, $p < 0.5$). As in the RLRD task therefore, there is no overall hemispheric difference in this task.

The distribution of errors in the left and right visual fields was then investigated in males versus females and stable versus unstable Dunlop Test responses. Table 3.7 shows the distributions found.

Although the trends were similar to those found on the RLRD task, no statistically significant effects of visual field were found in any condition. Both males and females, and stable and unstable Dunlop Test response groups made equal errors in the LVF-RH vs. RVF-LH condition. Hence, the visual field effect found in the RLRD task is not replicated in the SLRD task.

The results were categorised by both sex and stability of Dunlop Test responses. This is summarised in Tables 3.8a and b.

Table 3.8a

	<u>Females</u>	
	S	U
	62/297	94/302
R	20.9%	31.1%
	n = 28	n = 30
	80/358	113/358
L	22.3%	31.6%
	n = 28	n = 30

Table 3.8b

	<u>Males</u>	
	S	U
	145/705	161/549
R	20.6%	29.3%
	n = 61	n = 53
	168/728	167/575
L	23.1%	29.0%
	n = 61	n = 53

Table 3.8a and b - distribution of LVF-RH and RVF-LH conditions for stable and unstable Dunlop Test responses in males and females in the SLRD task. S - stable Dunlop Test responses, U - unstable Dunlop Test responses, R - RVF-LH condition, L - LVF-RH condition.

In this task, the only significant differences were found when comparing those with stable and unstable Dunlop Test responses. Hence, in all four conditions, females RVF-LH, males RVF-LH, females LVF-RH and males RVF-LH, the average error rate scored by those with unstable Dunlop Test responses was statistically higher than the error rate made by those with stable responses:

Female RVF-LH - $\chi^2 = 8.17$, DOF = 1, $p < 0.01$

Male RVF-LH - $\chi^2 = 12.83$, DOF = 1, $p < 0.001$

Female LVF-RH - $\chi^2 = 7.72$, DOF = 1, $p < 0.01$

Male LVF-RH - $\chi^2 = 5.99$, DOF = 1, $p < 0.02$.

To summarise these results: in the scanning right-left discrimination task, there were statistically significant differences found in the error rates scored by children with unstable Dunlop Test responses versus those with stable responses. The children with unstable responses made more errors in this task. No significant differences were found between males and females or between right and left visual fields in this test, however.

3.3.3 - LVF Advantage Versus RVF Advantage

In this section, the average percentage error of all subjects who made fewer errors in their left visual field was compared to that of subjects who made fewer errors in the right visual field. This analysis was carried out to investigate whether there were any advantages in the processing of this task if one or other hemisphere was used preferentially. To do this, the error rates of all children with LVF advantage were averaged together for each of the two paradigms - RLRD and SLRD. These were then compared to the average error scores for all the children who showed a RVF advantage on each

task.

This analysis showed that, for both the RLRD and SLRD tasks, children who had a RVFa were likely to make more errors than children with a LVFa -

RLRD - LVFa = 24.9% RVFa = 28.1%

($\chi^2 = 4.47$, DOF = 1, $p < 0.05$)

SLRD - LVFa = 25.4% RVFa = 29.8%

($\chi^2 = 8.08$, DOF = 1, $p < 0.01$)

This result provides further evidence in favour of the hypothesis that the visuospatial processing ability of the left hemisphere is inferior to that of the right.

How is this superiority of the LVFa subjects distributed with respect to visual field ? In order to investigate this question the error rate of the LVFa subjects in, for instance, the LVF has to be compared to the error rate of the RVFa subjects in their RVF. This will allow a comparison of the percentage errors made by the hemisphere which has been found to be superior at processing this task for any given subject. Tables 3.9a & b show the results of this analysis.

Inspection of tables 3.9a and b shows that subjects with a RVFa make more errors than subjects with LVFa in both their preferred visual field and in the opposite visual field. Hence, subjects who use the left hemisphere preferentially for processing this task (RVFa) make more errors both when processing stimuli which reach the preferred hemisphere first (targets in the RVF) and with those which reach the non-preferred hemisphere first. The difference between LVFa subjects and RVFa subjects is greater in the preferred visual field, however.

Table 3.9a - RLRD task

	LVF	RVF

LVFa	16.4%	33.6%

RVFa	37.2%	18.9%

Table 3.9b - SRLD task

	LVF	RVF

LVFa	17.1%	34.7%

RVFa	39.8%	18.9%

Table 3.9a & b - Distribution of errors in the LVF and RVF for subjects with LVFa and RVFa in each of the two paradigms - RLRD and SRLD.

Finally, the number of children with unstable Dunlop Test responses was compared between the LVFa and RVFa groups. This showed that in both paradigms the number of children with unstable Dunlop Test responses was larger in the group with RVFa.

RLRD - Unstable RVFa = 53.4%

Unstable LVFa = 45.5%

SRLD - Unstable RVFa = 52.1%

Unstable LVFa = 42.9%

This would suggest that some children with unstable Dunlop Test responses perform poorly on these tasks of dot localisation because they are using their left hemispheres preferentially for the processing of a spatial task. It appears that left hemisphere processing is inefficient - especially for targets appearing in the right visual field.

3.3.4 - Preliminary Investigations of Eye Movements

Seven subjects with stable Dunlop Test responses and seven children with unstable responses had their eye movements recorded during the

SLRD task. This preliminary trial was carried out to investigate whether the poor performance of the children with unstable responses to the Dunlop Test could be attributed to a greater instability of eye movement control.

Eye movements were recorded as described in the General Methods section of Chapter 2. A central calibration spot and two peripheral spots (9.5 degrees to each side) were used to assess the size of eye movement produced on the chart recorder per degree of real eye movement. As the calibration spots lay within the known linear range of the eye movement monitors, the size of the eye movement was easily calculated.

Table 3.10

Left Eye			Right Eye	
DT	number	size	number	size
S	1.20	3.75	0.80	2.48
S	0.76	3.59	0.88	2.64
S	1.75	17.40	3.25	7.70
S	2.21	6.17	1.32	4.54
S	1.58	6.66	1.42	8.49
S	2.90	15.03	2.85	14.94
S	3.35	13.86	3.55	21.80
mean	1.96	9.49	2.01	8.94
S.E.	0.34	2.18	0.44	2.69
U	5.17	31.83	5.33	32.12
U	3.43	21.00	4.00	17.24
U	2.07	7.80	2.57	6.77
U	4.47	22.97	4.73	19.48
U	2.63	13.65	2.67	11.62
U	3.39	18.88	3.89	14.56
U	1.68	10.81	1.95	10.00
mean	3.26	18.13	3.59	15.97
S.E.	0.47	3.09	0.47	3.15

Table 3.10 - Average number and size of eye movement per trial on the SLRD task. Results are averaged across seven subjects with either stable (S) or unstable (U) Dunlop Test responses for each eye.

Since the task requires the children to fixate steadily at a central point, any eye movements during the test are inappropriate. Hence, children who make eye movements during the task might be expected to perform less well than those with steady eye movement control. Hence, two measures of eye movement stability were used. First, the number of eye movements made during each trial was averaged for each subject. Secondly, the average size of the eye movements made during each trial was calculated for each subject. These values were calculated for each eye separately. Table 3.10 shows the results of this analysis.

Table 3.10 shows that the subjects with unstable Dunlop Test responses made more and larger inappropriate eye movements during this test than subjects with stable responses. The results for children with stable versus unstable Dunlop Test responses were compared using the student T-Test. There were statistically significant differences between the two groups on the number of movements per trial in both the right and the left eye (RE - $T = 2.46$, $DF = 12$, $p > 0.03$; LE - $T = 2.20$, $DF = 12$, $p > 0.049$). There was also a significant difference in the size of the eye movements made by the left eye ($T = 2.29$, $DF = 12$, $p > 0.043$). However, the difference in size of movements for the right eye only approached significance ($T = 1.70$, $DF = 12$, $p > 0.11$). Overall, the results suggest that, even with a small sample, it is possible to detect differences in the eye movement control on a dot localisation task of children with stable versus unstable Dunlop Test responses.

The difference in the error rate for the SLRD task was compared for the group with stable Dunlop Test responses versus those with unstable responses. As previously, the error rate for the children with unstable responses was higher (unstable - 25%; stable - 10.4%). This

unstable responses was higher (unstable - 25%; stable - 10.4%). This difference was found to be statistically significant ($\chi^2 = 5.63$, DOF 1, $p > 0.025$). Thus there is a correlation between the accuracy of eye movements on a spatial localisation task, the results of the Dunlop Test and the accuracy on the localisation task.

Since the preliminary study of eye movements during this task had been so successful, it had been hoped to extend this study, and to correlate the results with eye movements recorded during the Dunlop Test and with reading age. However, the computer used to control the tasks was stolen from the hospital just before the new study could be started, and so the proposed study was shelved.

3.4 - Discussion

The experiments described in this chapter were designed to investigate the ability of children with stable or unstable Dunlop Test responses to localise objects in space. It was argued that children with unstable Dunlop Test responses would be poorer at this task since their responses to the Dunlop Test suggest that they have difficulty in determining which eye to use for the assessment of visual direction. If the Dunlop Test is really an indicator of the ability to use one eye for the judgement of visual direction then children who fail to produce stable responses to the Dunlop Test should be less able to localise objects in space.

The results of both the RLRD and the SLRD tasks showed that the children with unstable Dunlop Test responses were significantly more likely to make errors than their stable counterparts. This is evidence in support of the hypothesis that the Dunlop Test is a measure of the ability to judge visual direction accurately.

Developmental trends were found for both the RLRD and the SLRD

grew older. This corresponded to the developmental curves previously found for the development of stability on the Dunlop Test (Stein, Riddell & Fowler, 1986).

Differences were found in the abilities of males and females in the RLRD task. Females were found to be less proficient at this task than the males tested. This concurs with previous reports of male superiority on tasks involving the spatial domain (McGee, 1979). This difference could be shown to be confined to the children with unstable Dunlop Test responses. Males and females with stable Dunlop Test responses had similar average error rates. This would suggest that females might be particularly at risk for reading difficulties if their Dunlop Test responses are unstable. This finding is supported by evidence presented by Stein and Fowler (1985) which suggested that female dyslexics were more likely to have unstable Dunlop Test responses than their male counterparts.

The nature of the task allowed the investigation of the contribution made by each hemisphere to the processing. In the RLRD task there were significant differences in the abilities of the right and left hemispheres (as indicated by the left and right visual fields respectively) when sex and Dunlop Test stability were considered. Specifically, unstable females make more errors than their stable counterparts in both visual fields whereas unstable males make more errors mostly in the LVF-RH condition as compared to stable males. This difference can be related to the postulated differences of hemispheric specialisation for males and females: it has been suggested that males have a greater lateralisation of function than females (Springer & Deutsch, 1985). Males are thought to process language based tasks using the left hemisphere and spatial tasks using the right whereas there is thought to be more overlap of function

between the hemispheres in females. In the task described in this chapter, the females were found to have less lateralised errors than the males suggesting that whatever is affecting the ability to locate small objects in space is operating not only in one hemisphere, but wherever visuospatial function is processed.

None of the differences found between males and females or children with stable and unstable Dunlop Test responses in each visual field were significant in the SLRD task, although they were in the same direction as those found in the RLRD task. The difference between the two tasks is that a consistent left to right scanning pattern is imposed on the eye movements in the SLRD task. Saccadic movements of the eyes from right to left are controlled by the right hemisphere. It has been suggested that preferential activation of one or other hemisphere can increase the accuracy of the processing on that side (Springer & Deutsch, 1985). In this case, activation of the right hemisphere by the imposition of a consistent scanning pattern might decrease the error rate on that side. This might lead to the more even distribution of errors between visual fields found in this task.

Some differences between the ability of the two hemispheres in their spatial processing was found for the SLRD task however, in addition to those found in the RLRD task, when the children were divided into groups according to their more accurate visual field. The children who favoured the RVF-LH (RVFa) were found to have a higher overall error rate in both tasks. This was not confined to the non-preferred field i.e. when the LVF of RVFa children was compared to the RVF of LVFa children, the RVFa children made more errors. This was also true of a comparison between the RVF of RVFa children and the LVF of LVFa children. Hence processing by the left hemisphere appears to be less efficient for both the stimuli which arrive first in that

hemisphere and for those which have to cross using the cerebral commissures. This analysis also showed that more children with unstable reference showed a RVFa - or inferior left hemisphere processing for a spatial task.

The differences in the abilities of the hemispheres to process this task, though significant, are small. There is a possible reason for this. These tasks involved the central 1.5 degrees of visual space. This visual area is dually represented in each hemispheres by corpus callosal connections and by projections arising from naso-temporal overlap of ganglion cells in the retina (Bunt, Minckler & Johanson, 1977, Hubel & Wiesel, 1967, Kennedy, Martin, Orban & Whitteridge, 1985, Leicester, 1968, Payne, 1986, Stone, Leicester & Sherman, 1973). If degradation of the stimulus as it passes across the corpus callosum is a causal factor in the differences detected between the hemispheres, smaller differences between the hemispheres would be expected in this area of the visual field. It would be interesting to repeat this experiment at different eccentricities to determine the relative contributions of the connections between the visual fields to these differences.

A preliminary study also showed that there is a correlation between the stability of the eye movements during the SLRD task and the stability of Dunlop Test responses. Children with unstable Dunlop Test responses made more and larger eye movements in both eyes than their stable counterparts. The preliminary nature of this investigation, however, prevents any comment on the direction of correlation; i.e. do the unsteady eye movements cause the poor visual direction sense and the instability of the Dunlop Test or is the poor visual direction sense the cause of the unstable eye movements? The results from chapter 2 in which it was shown that children with unstable Dunlop

Test responses also showed poor control of vergence eye movements, would give credence to the suggestion that the poor eye movements are the causal factor in both the poor performance on the spatial localisation tasks and the instability of the Dunlop Test responses. However, this relationship needs further investigation. It would also be interesting to examine the relationship between reading and the ability to judge correctly the location of objects in space.

To summarise, the results of the experiments presented in this chapter suggest that children with unstable Dunlop Test responses are less able to judge visual direction accurately than children with stable responses. As more errors are made by children with a RVF advantage than those with a LVF advantage it would seem that the left hemisphere is less efficient at processing this task. More children with unstable Dunlop Test responses showed RVFa.

Males and females with unstable responses to the Dunlop Test showed differential abilities in the left and right visual fields. While the males made more errors in the LVF only, the females were found to make more errors in both visual fields. This was linked to the suggestion that females are less lateralised at spatial tasks than males.

Finally it was shown that there is a correlation between the number and size of eye movements made during this task, and the stability of the Dunlop Test responses. Since the children with unstable Dunlop Test responses also made significantly more errors on the spatial localisation task than their stable counterparts, this might suggest that the instability of the eye movements causes both the poor performance in the spatial localisation task and the instability of the Dunlop Test responses.

Chapter 4 - Longitudinal Study of a Cohort of Primary School Children

4.1 - Introduction

This chapter describes a longitudinal study of one class of children who were followed for four years - from the first week they started in infant school until their first year in junior school. Measurements were made once every year. The study was designed to investigate the development of Dunlop Test stability, stereoacuity and vergence eye movements in a cross section of children and to compare these measures with their reading development. Measures of Dunlop Test stability, vergence eye movement control and stereoacuity were made, as well as of reading age, spelling age and IQ measures. These investigations allowed me to assess how far the Dunlop test, eye movement recording and other ophthalmological measures can be used to predict the ease with which a child will learn to read.

Simple measures of auditory ability (rhyming and alliteration) and sequencing ability (saying the days of the week and the months of the year in correct order) were used to test phonemic segmentation and sequencing abilities. These scores allowed a comparison between the predictive ability of tasks involving auditory or sequencing skills with those of the Dunlop test which assesses visuomotor ability.

Stein, Riddell and Fowler (1986) suggested that a correlation existed between the development of Dunlop Test stability and reading ability. They studied a large population of unselected primary school children aged from 5 to 11 years old. They found that the proportion of children with stable Dunlop Test responses increased with age. Their results also showed that those children who had failed to develop stable Dunlop Test responses were poorer at reading than those children whose responses were stable. Their observations did not

allow them to determine the relationship between the length of time taken for stable responses to develop, and reading ability since the study was not longitudinal. However, as in the present study, responses to the Dunlop Test and reading age were measured on more than one occasion, I hoped to investigate links between age of development of stability and reading ability.

A major criticism of studies in which the role of Dunlop Test stability in learning to read has been investigated is that it is difficult to separate cause and effect. A correlation between improvement in reading age and development of stability is insufficient evidence to prove that this development is a prerequisite of learning to read. It can only suggest a link between the two skills. In fact it has been argued that the process of learning to read fluently may be what produces vergence stability. In the present study however measurements were made before most of the children had any reading experience whatsoever. It was hoped that following the time course of these events more precisely would enable separation of cause and effect.

Stereoacuity was also measured at each visit in order to investigate the developmental trend for this skill. Since fine judgement of depth requires accurate and steady binocular fixation, children with unstable Dunlop Test responses might be expected to show poorer stereoacuity than their stable counterparts. Hence, comparisons between stability of Dunlop Test responses and stereoacuity were also made.

The results of these investigations suggest that both Dunlop Test responses and vergence eye movements are correlated with reading and spelling ability. Clear developmental trends for stability of the Dunlop Test, vergence eye movements and stereoacuity were found. All

the children in this cohort who showed reading difficulties were found to be affected by a delay in the development of stable vergence eye movement control and/or to suffer auditory and sequencing difficulties. The results suggest that the investigation of vergence eye movement control could be a useful tool, in combination with other tests, for identifying children who are 'at risk' of failing to learn to read.

4.2 - Subjects and Methods

The subjects for this study were the 1984 first year intake of Ascot Heath Infant School. There were 45 children in the class, one of whom was excluded since he was found to have other visual problems. At each visit, the number of children tested decreased because of absence due to illness or change of address. Hence only 29 children could be tested on all four visits to the school. Some general results have been calculated using the data on all the children tested in each year. In these cases, the number of subjects is quoted. All other results are calculated from the data obtained on only the 29 children who completed the study.

The children were given a full orthoptic assessment as described in the General Methods (Section 2.2.1). This included the Randot test of stereoacuity, the Dunlop test and recording vergence eye movements in the synoptophore, using infra red reflectometry (Section 2.2). The slides used for these measurements were the house slides (see Figure 2.5), and two sizes of the rabbit (Clement Clarke fusion slides F 119 & F 120, and F 65 & F 66). The scoring systems used for stability of Dunlop Test responses and vergence eye movement control are also described in the General Methods (Section 2.2.4).

On the third visit (i.e. when the children were 6-7 years old) all

children were assessed using the Matrices and Similarities sub-tests of the British Ability Scales (BAS) (Thomson, 1982). The word reading sub-test from the BAS and a short spelling test were also given, both on this occasion and on the following visit. The spelling test used involved writing one sentence of 11 words on the first testing, and three sentences totalling 21 words on the second. These tests were scored for the number of words spelt correctly.

A short test of auditory capability was also administered on the third visit in an attempt to predict reading difficulties associated with auditory dysfunction. This test involved saying 5 rhyming words and 5 words with the same starting letter, as words which were presented orally by the examiner. The children were scored for each correct response for each test. This gave a maximum possible score of 10 for the combined auditory tests.

The children were also given a simple sequencing test. In this they were asked to say the days of the week and the months of the year in the correct order. Scoring was again on the basis of the number of correct responses made, a point being deducted for each error made. The total possible score in this test was therefore 19.

The ages of the children seen on the first visit ranged from 4yrs 9mths to 5yrs 4mths. For the analysis they were split into two groups:

i) those who were not yet 5yrs - i.e. those aged 4yrs 9mths to 4yrs 11mths.

and ii) those who were 5 yrs or older - 5yrs 0mths to 5yrs 4mths.

Group i consisted of 17 children with an average age of 4yrs 10mths.

Group ii contained 26 children with an average age of 5yrs 2mths. The children were kept in these groupings on follow-up visits.

DEVELOPMENT OF STABLE DUNLOP TEST RESPONSES

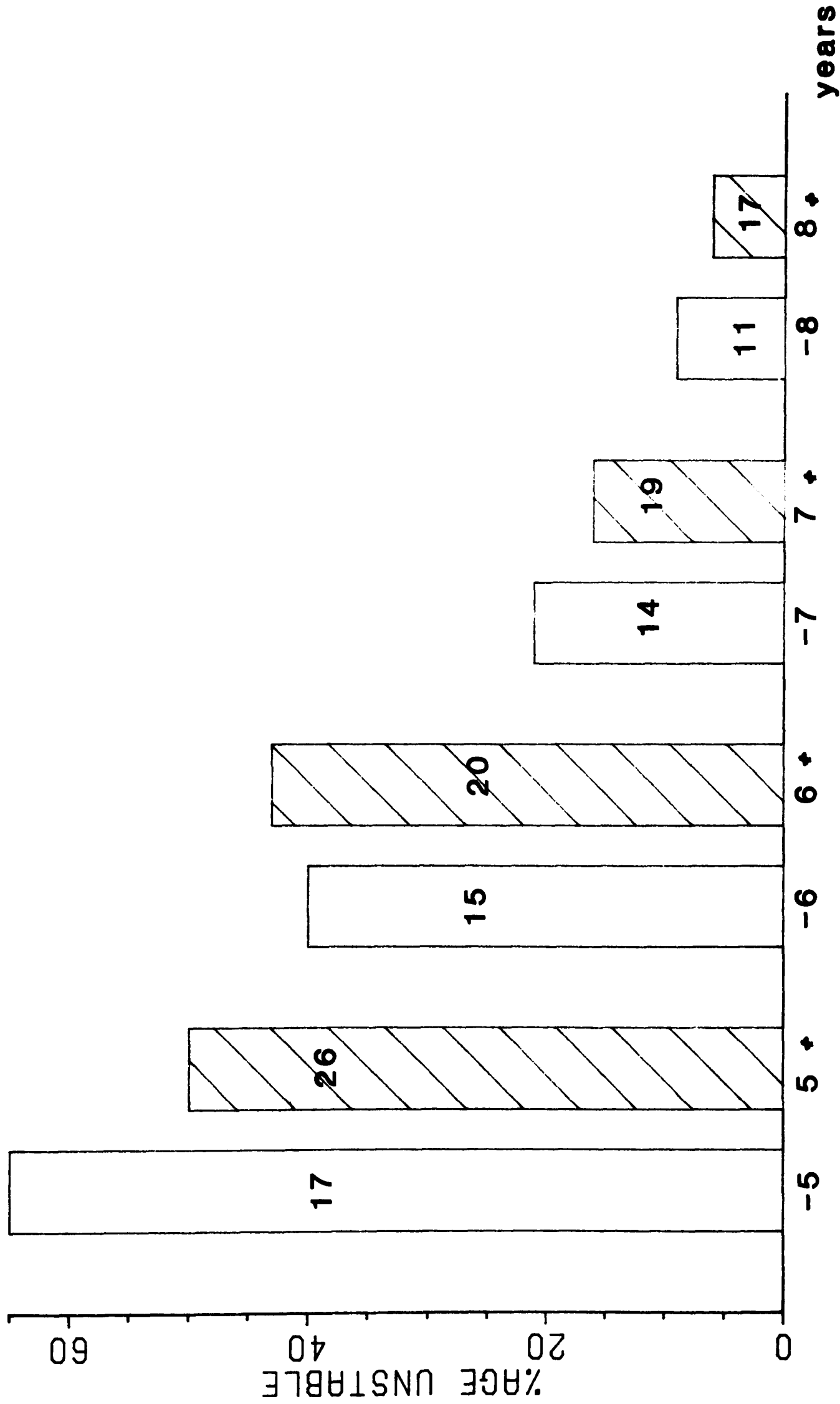


Figure 4.1 - Bar chart showing the percentage of children at different ages with stable Dunlop Test responses. The chart demonstrates the developmental trend for the acquisition of Dunlop Test stability. The number of children tested at each age level is shown.

4.3 - Results

4.3.1 - Development of Dunlop Test Stability

Figure 4.1 shows the development of stable Dunlop Test responses in these children. For ease of comparison with other developmental trends this has been plotted as a bar chart of the percentage of children with unstable responses at each age level. The shaded bars show the older group for each year. Comparison of the first two bars shows that even during their first week in school there was a trend suggesting that older children were more likely to have developed stable responses to the Dunlop Test than younger children (35% of younger children had stable responses as compared with 50% of the older children). This trend continued on subsequent testings. However, none of the differences between groups at each testing were found to be statistically significant. The stronger trend occurred between each testing. At 5yrs old over 50% of the children had unstable responses, while at 8yrs less than 15% of the children showed this instability.

It was to be expected that the change between testings would be greater than the difference between the two groups measured during one visit. The difference in average age between testings was 1 year whereas the average intra-group difference was only 4 months.

The results show that development of a stable Dunlop Test responses preceded reading experience. This supports the hypothesis that the development of stable responses aids the development of reading skills. The results do not, however, rule out the possibility that experience of print may contribute to the development of such stability in children who have not developed stable responses before attending school.

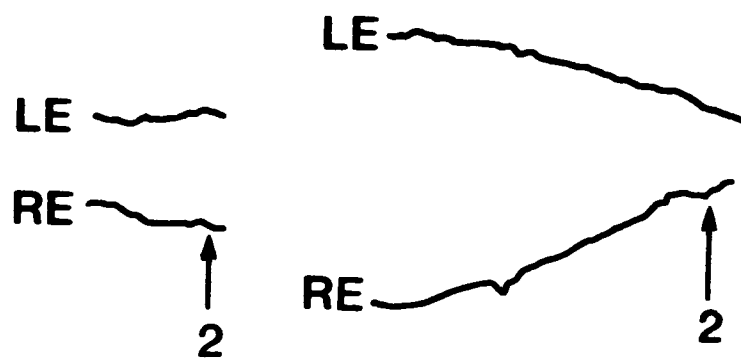
A

A.McD.

$2\frac{1}{2}^{\circ}$ fusion targets

Divergence

Convergence



7° fusion targets

Convergence

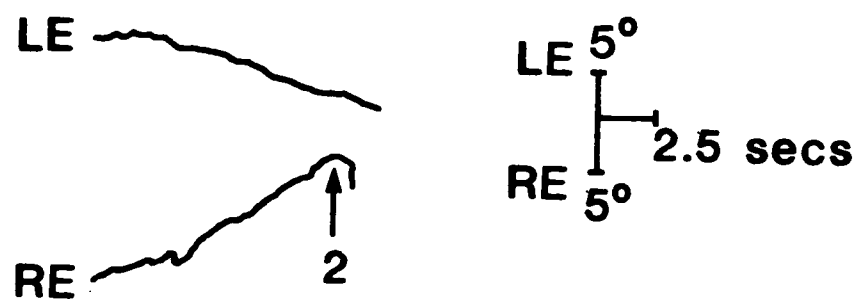


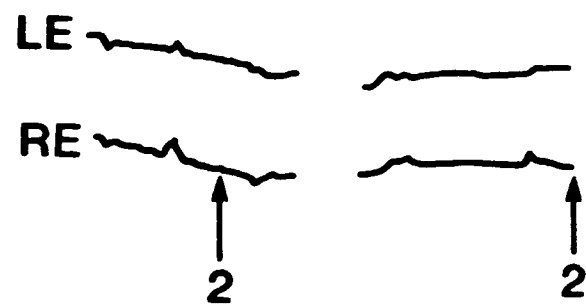
Figure 4.2a - Vergence eye movements recorded using infra-red reflectome try during convergence and divergence of the synoptophore tubes. The subject was a 6 year old male normal reader. The fusional stimuli used were the modified Dunlop Test slides and the small rabbits. Key: LE - left eye; RE - right eye; 2 - point at which child reported that fusion had broken.

B

WP

$2\frac{1}{2}^{\circ}$ fusion targets

Divergence Convergence



7° fusion targets

Convergence

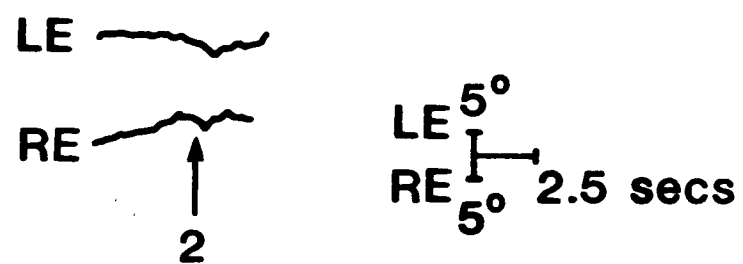


Figure 4.2b - Vergence eye movements recorded as above in a 6 year old dyslexic boy.

4.3.2 - Development of Stable Vergence Eye Movement Control

Eye movements were recorded on all but the first visit. Figure 4.2a shows an example of stable eye movements. These were recorded from a 6 year old boy. The 's' marks the point at which the movement of the synoptophore tubes began and the '2' marks the point at which the child reported that he could see two houses (i.e. diplopia had occurred). Diplopia occurs when the targets no longer lie within Panum's area.

The figure shows one divergence movement recorded using the Dunlop test targets. Three convergence movements, recorded using different sizes of target, are also shown. The targets for these measurements were the Dunlop test slides, the macular sized rabbit and the larger para-foveal sized rabbit.

The eye movements recorded during divergence show that the subject followed the target for about 3 degrees of divergence. The eye movements were smooth and obviously disconjugate. During convergence, eye movements were symmetrical and disconjugate and the target was followed for around 20 degrees of vergence.

In figure 4.2b vergence eye movement recordings are shown for one of the six year old boys who was found to have unstable vergence control. The abbreviations are the same as in Figure 4.2a. During divergence, this subject's eyes moved conjugately and diplopia occurred very quickly i.e. the eyes did not react properly to the movement of the targets across the retinae. Possibly there was visual suppression of the target appearing in the right eye, although the subject did not report that either of the posts disappeared. It would appear, since no vergence eye movements were made, that the target stayed fused only for the length of time taken for it to reach the boundaries of Panum's area.

DEVELOPMENT OF VERGENCE CONTROL

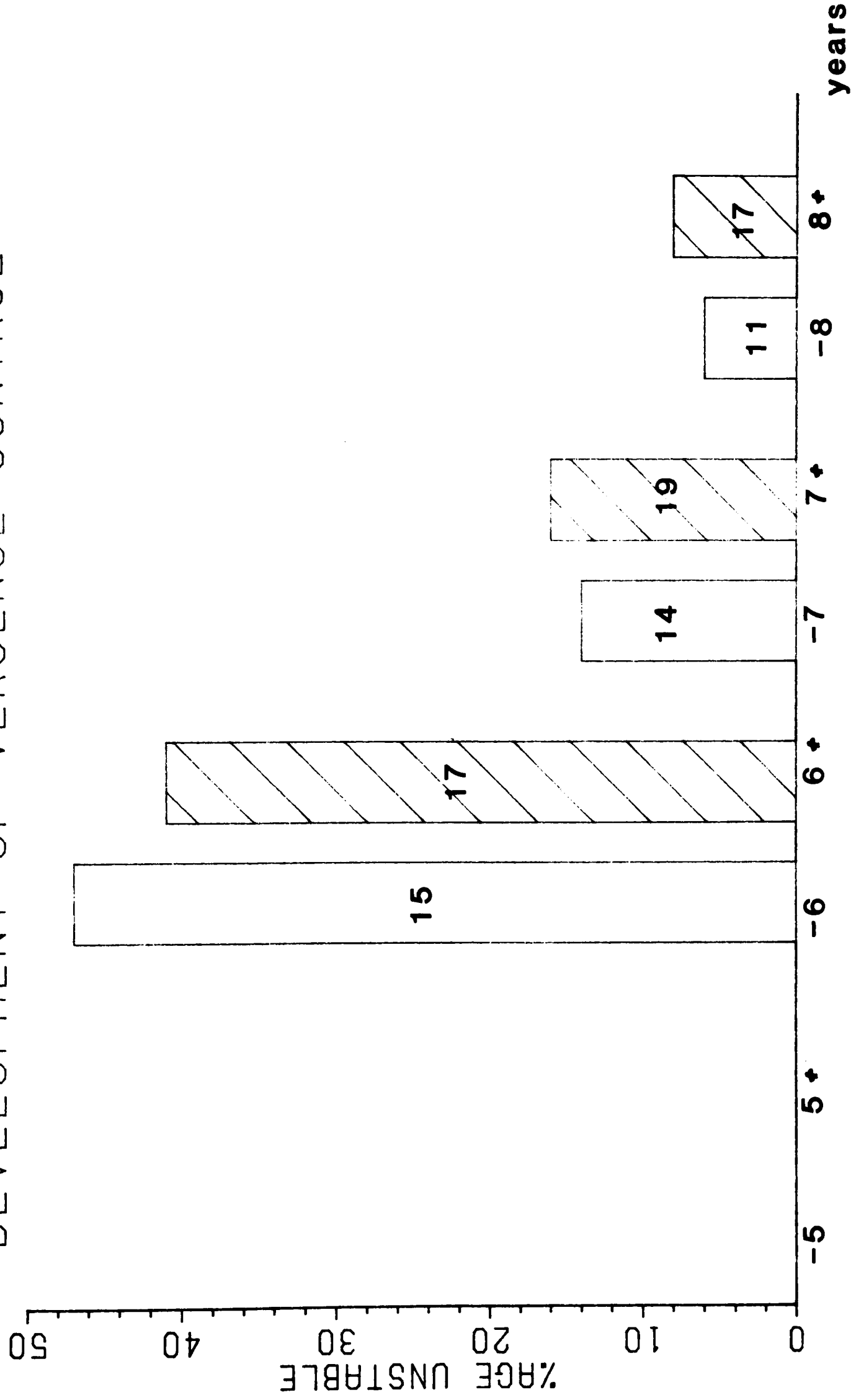


Figure 4.3 - Bar chart showing the percentage of children at different ages with stable vergence eye movements. The chart demonstrates the developmental trend for the acquisition of vergence stability. The number of children tested at each age level is shown.

During convergence using the Dunlop test targets, a small vergence eye movement was elicited. However, despite the fact that the subject appeared to respond appropriately, diplopia was soon reported. The tracking did not appear to have been rapid enough to maintain the targets within Panum's fusional area.

The eye movements produced during movement of the macular and parafoveal targets did not elicit appropriate movements of the eyes. In both cases the movements were conjugate. Examination of the eye movements produced while tracking the parafoveal targets showed that the eyes moved first to the left and then to the right. If this conjugate movement was the result of visual suppression, then it must have switched from one eye to the other.

The developmental trend for stability of eye movement control is shown in Figure 4.3. The graph takes the same form as the previous developmental curve, though no data was available for the first visit. Again, the trend is for increasing stability to develop with age.

In both figures 4.1 and 4.3 the greatest improvement occurred between 6 and 7 years. The similarity in these graphs suggests that changes in stability of Dunlop Test responses are reflected in changes in the stability of eye movement recordings. This provides further evidence for the theory that stable Dunlop Test responses concord with stability of vergence eye movement control.

4.3.3 - Development of Stereoacuity

Figure 4.4 shows the development of stereoacuity plotted in a similar manner to the development of stable Dunlop Test responses. Error bars show the standard error for each group. Again the trend was for stereoacuity to become more accurate with age. Thus at 5 years the smallest average disparity detectable was 64 seconds of arc while at 8

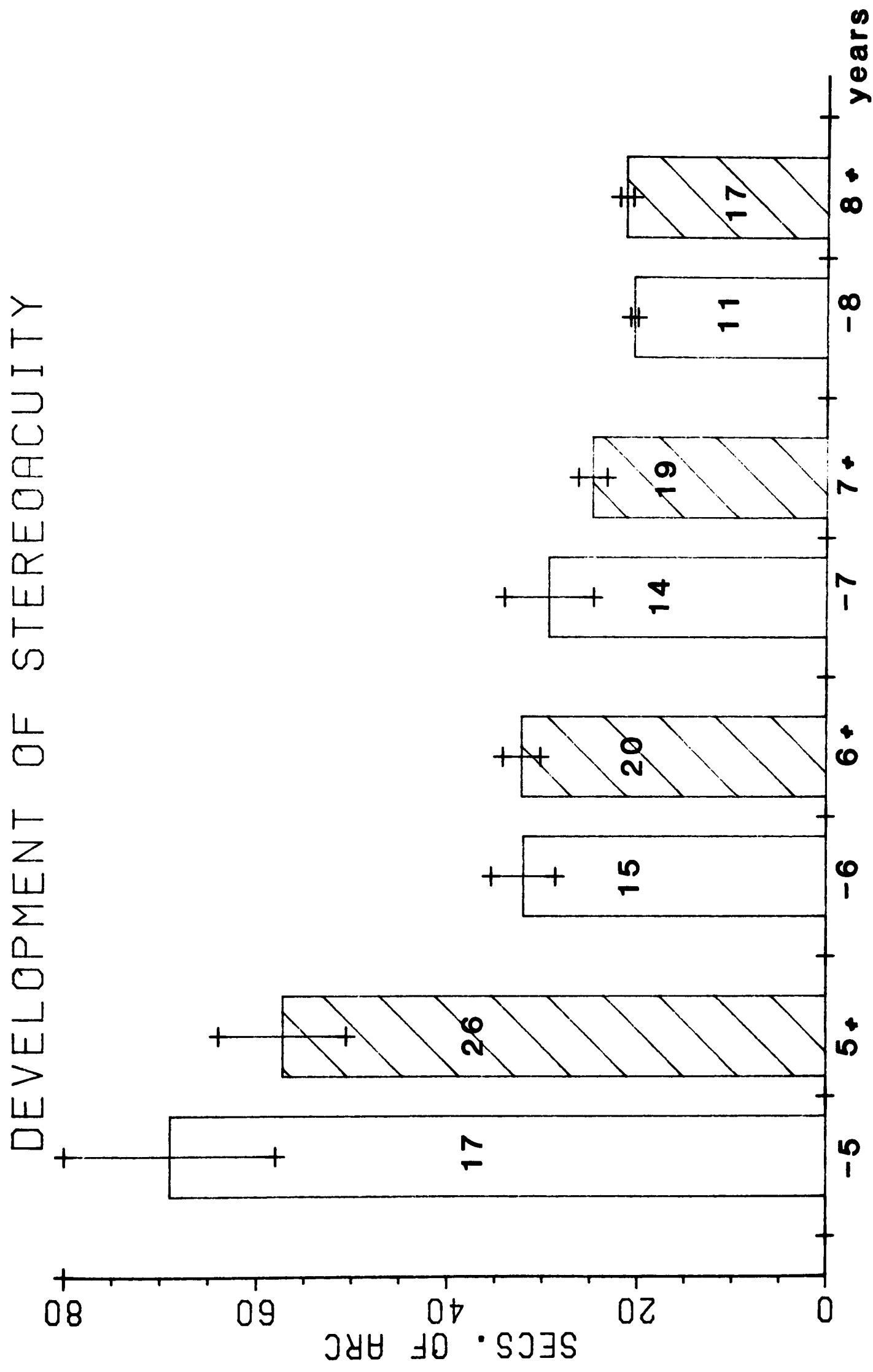


Figure 4.4 - Bar chart showing the stereoacuity measured in seconds of arc for children at different ages. The chart demonstrates the developmental trend for the acquisition of fine stereopsis. The number of children tested at each age level is shown. Standard error bars are given.

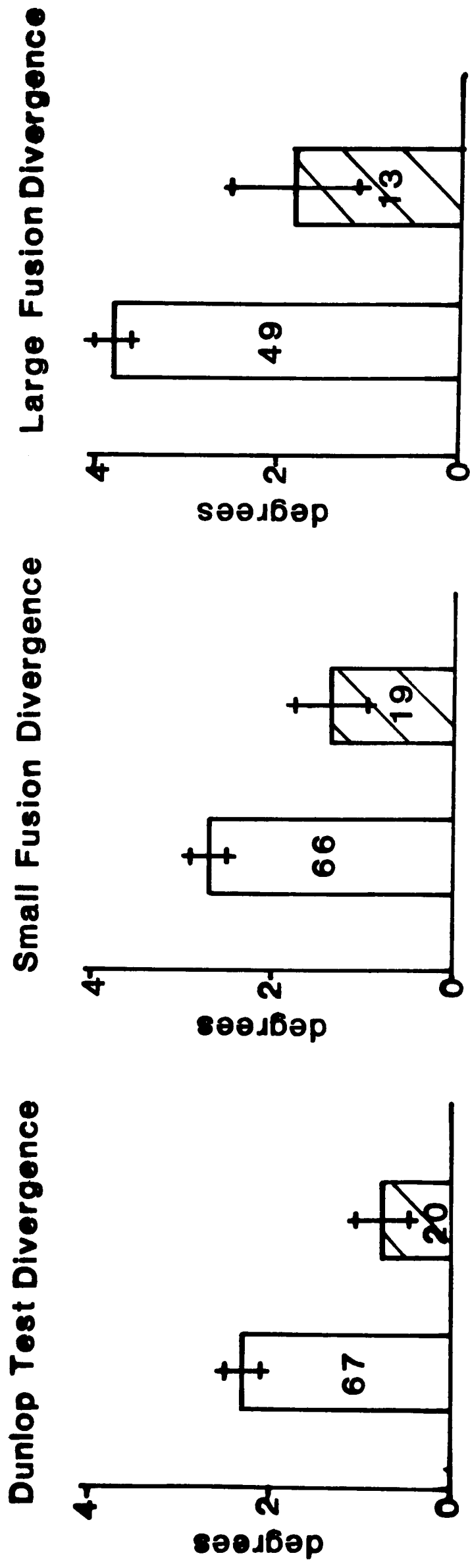
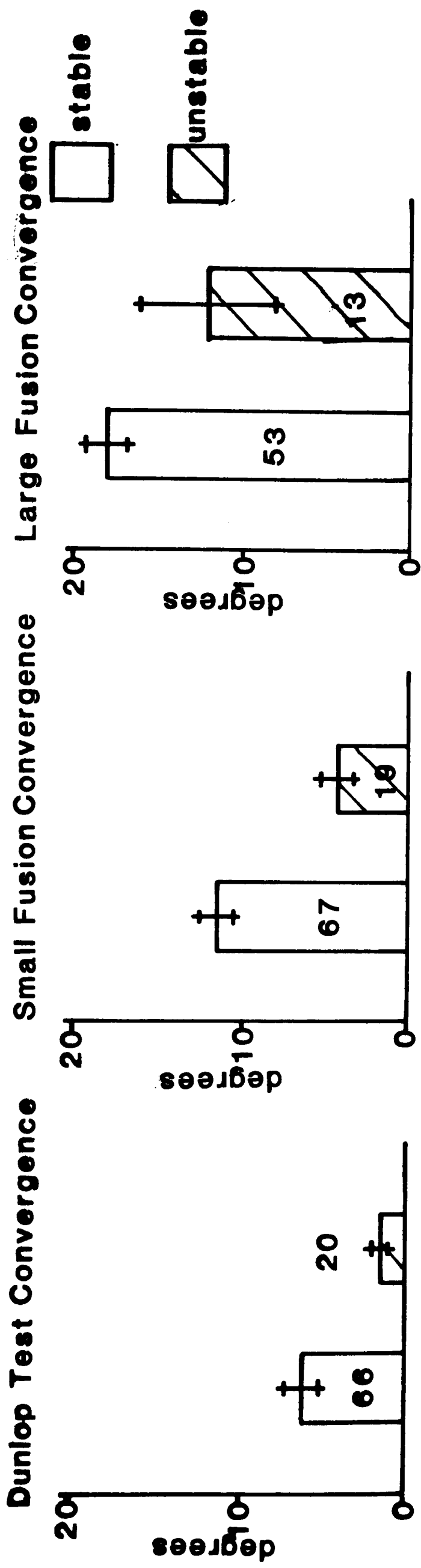


Figure 4.5 - Bar chart showing the amplitude of fusion measured for three target sizes (2 x 1.5 degs., 2.5 x 2.5 degs., and 7 x 7 degs.) in children with stable and unstable Dunlop Test responses. Standard error bars are give.

years this had improved to 20.5 seconds of arc. Unfortunately, the test has a ceiling value of 20 seconds of arc. Nevertheless the results show that, while 5 year olds cannot detect very small disparities, by 8 years old the majority of children in a normal population have developed full stereoacuity.

4.3.4 - Vergence Eye Movements and Dunlop Test Stability

Figure 4.5 shows the relationship between the range of vergence movements over which fusion was maintained and the stability of vergence eye movement control as revealed by the Dunlop Test. The results are plotted for three different sizes of target. Children have been grouped according to size of target and stability of eye movement control. The shaded bars show the children with unstable eye movement control. Error bars show the standard error for each group.

The fusional amplitude for convergent movements was larger than for divergent movements in all cases. This is to be expected since all testing began with the eyes at the angle of fusion. From this point, most subjects have a much larger range of convergence, needed to attend to objects lying closer to them than optical infinity, than of divergence which is never required in practice.

The range of fusion also increased with increasing target size. As target size was increased the accuracy of eye movement control required to maintain the target on the fovea decreased. Hence, the smallest target was likely to appear double if small, inappropriate, conjugate movements were made during vergence tracking, whereas for large targets this would not occur. Also, Panum's fusional area is thought to increase in size in the periphery (Cashell and Durran, 1981) so that, as the size of the target is increased, the amount of slippage between corresponding retinal points permissible before the

DEVELOPMENT OF STEREOACUITY

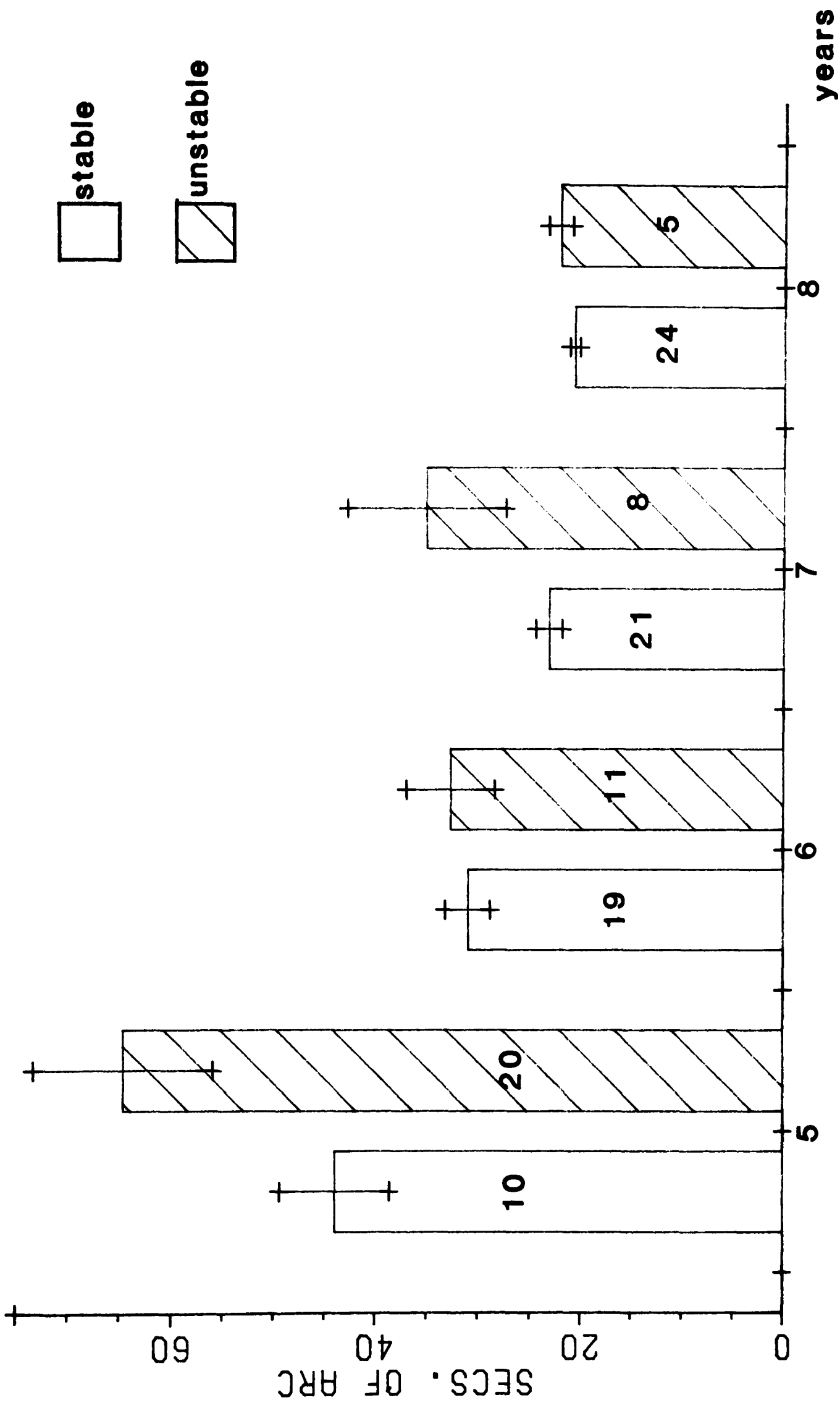


Figure 4.6 - Bar chart comparing the developmental trend for acquisition of fine stereopsis in children with stable and unstable Dunlop Test responses. The number of children tested at each level is shown. Standard error bars are given.

onset of diplopia, also increases. This may help to explain the increasing range of fusion found on increasing target size.

For all conditions, children with unstable vergence control were found to have a smaller range of fusional amplitudes than children with stable control. The assessment of vergence stability was made from the eye movements recorded with the Dunlop test targets only. Thus increasing fusional amplitude will be expected for measurements made during this condition. However, Figure 4.5 shows that this relationship also holds for the larger targets, in both convergence and divergence.

4.3.5 - Stereoacuity and Dunlop Test Stability

The similarity of the developmental trends for stereoacuity and stability of Dunlop Test responses suggests that there could be a functional correlation between this stability and the ability to detect small disparities in depth. If such a correlation exists, children, at all age, levels who had developed stable Dunlop Test responses should be capable of detecting smaller depth disparities than those who had not.

Figure 4.6 shows the results of a comparison between stereoacuity measurements in children with stable and unstable Dunlop Test responses. Again the trend for improving stereoacuity with age is evident. This trend was stronger in the children with stable Dunlop Test responses than it was in those with unstable responses.

The stereoacuity of children with stable Dunlop Test responses was higher at each age level than that of children who had not yet developed stable control. The difference was greatest in the younger children, since by 8 years old, there were fewer children with unstable reference, and stereoacuity was reaching the limits of the

Reading Age at 7 years

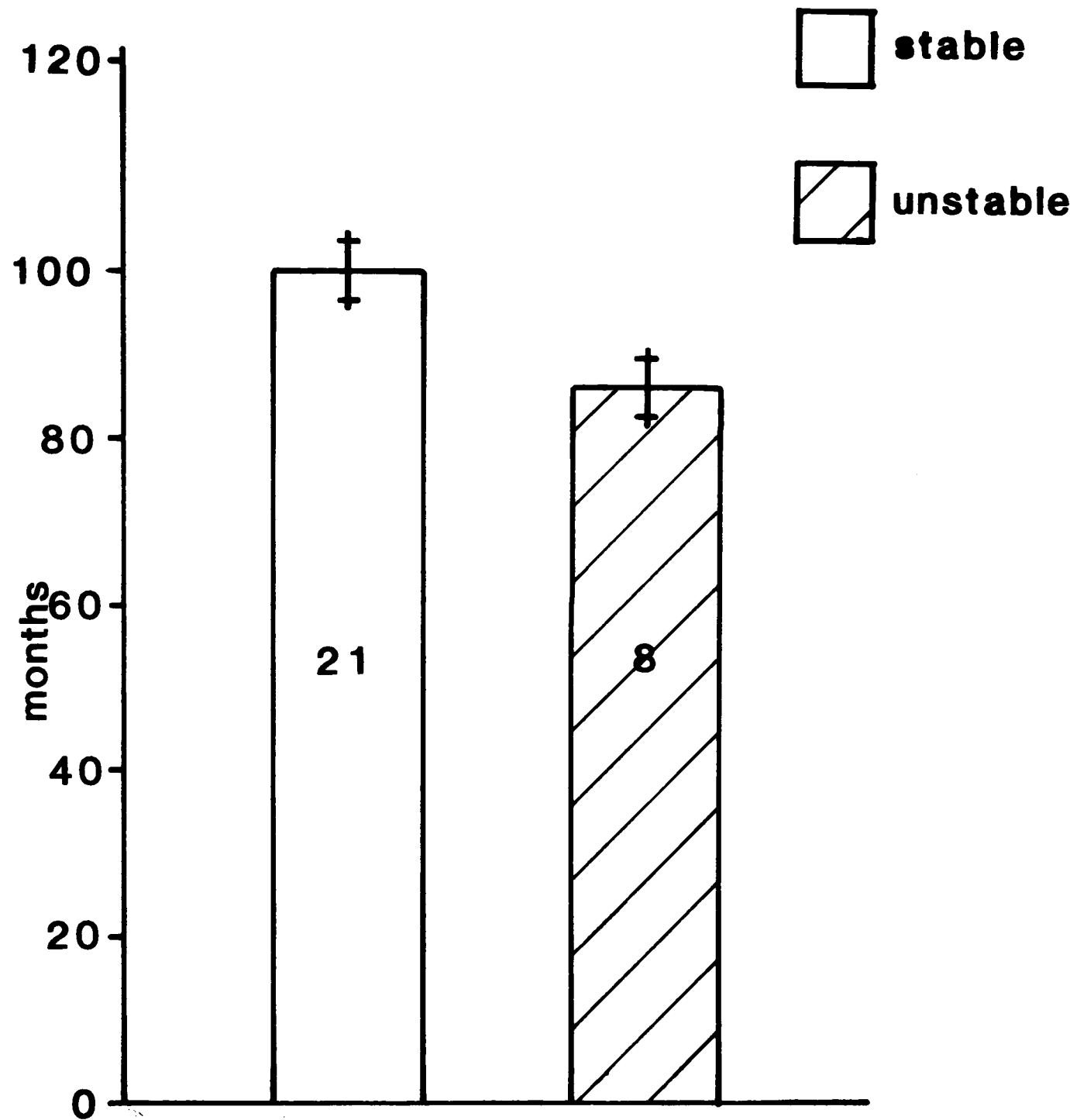


Figure 4.7a - Bar chart showing the reading ages of 7 year old children with stable compared with unstable Dunlop Test responses. The number of children tested is shown. Standard error bars are given.

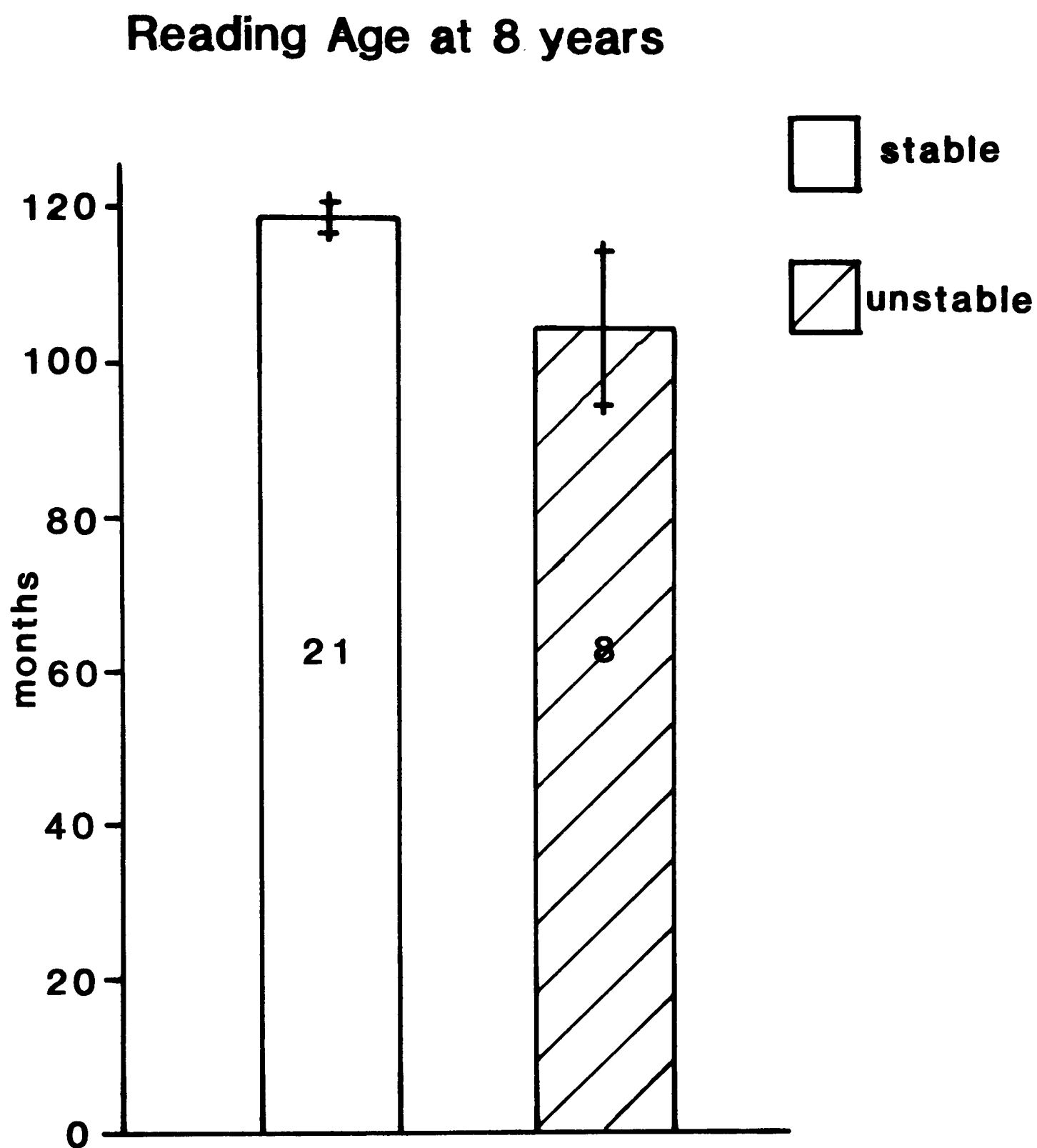


Figure 4.7b - Bar chart showing the reading ages measured at 8 years of children with stable compared with unstable Dunlop Test responses measured at 7 years. The children who had unstable Dunlop Test responses at 7 years have a lower reading ability at 8 years than those who had stable Dunlop Test responses at this time. This demonstrates the predictive ability of the Dunlop Test. The number of children tested is shown. Standard error bars are given.

test. The number of subjects tested however was too small for the differences to reach statistical significance. A larger study would be required to confirm the trend suggested by these results. Despite this, the results do suggest that stability of Dunlop Test responses could be a prerequisite for detection of small depth disparities.

4.3.6 - Dunlop Test Responses and Reading Ability

A correlation has also been suggested between the development of stable Dunlop Test responses and improved reading in normal children (Stein, Riddell and Fowler, 1985, Bigelow and McKenzie, 1985) and in dyslexics (Stein and Fowler, 1981, 1985). In Figure 4.7a & b the reading ages of those with stable Dunlop Test responses are compared with those with unstable responses. Figure 4.7a makes this comparison at 7 years of age. The error bars show standard errors for each group. It can be seen that, for the group as a whole, the average reading age was higher than the chronological age. However, the 8 children who failed to develop stable responses had an average reading age which was more than 1 year behind the average for the stable group. This result was statistically significant ($T = 2.07$, $DOF = 27$, $p < 0.05$).

Figure 4.7b demonstrates the predictive ability of the Dunlop Test. In this figure, the Dunlop Test responses measured at 7 years old are compared with the reading age measured at 8 years. Again, the average reading age of the whole group was above the average chronological age. But the average reading age of the unstable children was more than a year behind that found for the stable group. This difference was not statistically significant however ($T = 1.32$, $DOF = 27$, $p < 0.19$). This was probably due to the small sample number and the large variance of the measured reading ages. A larger sample might show a clearer prediction. However, the trend suggests that unstable Dunlop

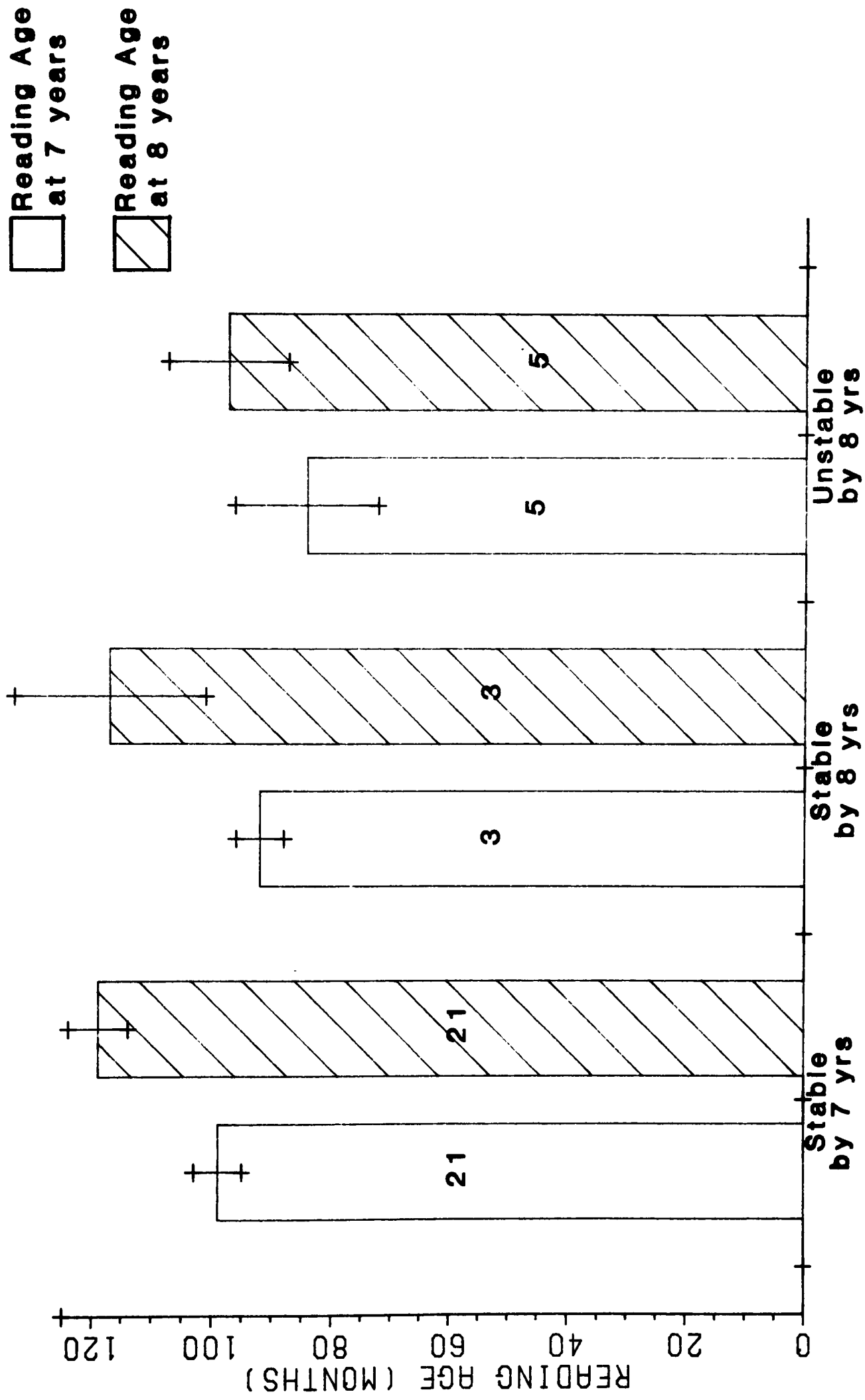


Figure 4.8 - Bar chart showing the reading ability of children measured at 7 and 8 years as a function of the age at which the children developed stable Dunlop Test responses. The trend shows that the later this stability is acquired, the poorer the reading ability. The number of children tested is shown. Standard error bars are given.

Test responses may predict a group of children who will have reading difficulties one year later.

Another way of looking at the predictive ability of the Dunlop Test is to examine the reading ages of children as they develop stable responses. Figure 4.8 shows the reading ages measured at 7 and 8 years for three groups of children. The first group had developed stable Dunlop Test responses by 7 years, the second group had stable responses at 8 years, the third group had not developed stability by the end of the study. The results show that the children who developed stable reference earliest (at 7 yrs) had the highest reading age measured at 7 years. Children who had developed stability by 8 years had the same reading ability measured at 8 yrs as the group who gained stability at 7 yrs. The average reading age of the group who remained unstable throughout the study was lower at both 7yrs and 8 yrs. There is a clear trend for reading ability to improve as the age at which stable Dunlop Test responses develop decreases.

4.3.7 - Reading Age Interactions with the Dunlop Test

Learning to read is a process which is dependent on interactions between auditory and visual input. Several studies (Bryant and Bradley, 1986, Snowling, 1987) have shown that many dyslexic children have impairments in phonological processing. Other studies (Pavlidis, 1981, Stein, Riddell & Fowler, 1986) have suggested that the control of eye movements might prevent children from learning to read effectively. This study gave an opportunity to investigate the interactions between the ability to perform a phonemic segmentation task and Dunlop Test stability. The results of a short sequencing task were also considered.

Table 4.1 shows the results of all tests for children with stable

compared with unstable Dunlop Test responses.

Table 4.1.

Test	Stable (n = 21)		Unstable (n = 8)		T	p <
	mean	S.E.	mean	S.E.		
Similarities	61.7	1.42	61.2	1.93	0.16	0.90
Matrices	59.9	1.30	53.2	2.41	2.58	0.02
Auditory	9.14	0.28	7.75	0.88	1.99	0.06
Sequencing	18.3	0.27	17.9	0.64	0.78	0.44
Stereoacuity	23.1	1.36	35.6	7.58	2.47	0.02
Reading Age	8,2	,4	7,2	,4	2.07	0.05
Spelling	8.52	0.39	7.25	1.22	1.31	0.20

Table 4.1 - Scores for seven year old children with stable versus unstable Dunlop Test responses.

The results in Table 4.1 show that children with unstable Dunlop Test responses had a significantly lower reading ability than children with stable responses. The spelling of the unstable children was also poorer although this did not reach statistical significance. These differences cannot be attributed purely to poor phonemic segmentation since, even though the difference between the two groups did not reach statistical significance, children with unstable Dunlop Test responses scored poorly on the auditory test. The only other tests in which there was a statistically significant difference between the two groups were the Matrices subtest of the British Abilities Scales and the stereoacuity test. The children with unstable Dunlop Test responses were poorer at both these tests. A possible reason for the poorer score of the unstable children on the Matrices sub-test is that the test required accurate spatial perception; the children had to

detect and complete a visual pattern. It is unlikely that these children were less intelligent than the children with stable Dunlop Test responses since both groups performed equally well on a verbal sub-test of the BAS - Similarities. Similarly, accurate stereopsis also required the children to have developed stable perceptions of visual space.

Hence the children with unstable Dunlop Test responses had poorer reading ability than the children with stable responses. These differences were not only related to an inability to segment phonemes, but were also probably related to poor visuospatial representation.

In an attempt to separate the effects of poor phonemic segmentation from poor visuospatial representations, the reading age of children with high scores on the test of phonemic segmentation and with stable Dunlop Test responses was compared to that of children who scored poorly on one or both of the tests. A cut-off score of 7 was used to divide children with average or above auditory score from those with poor phonemic segmentation abilities. A score of 7 was chosen since nearly 80% of the children scored above this. Children scoring 7 or less were considered to show poor phonemic processing ability. Figure 4.9 shows the results of this analysis. The children with the highest reading ability were those with both a high score on the test of phonemic segmentation and stable responses on the Dunlop Test (8 yrs 5mths). Those with a low score on only one test showed intermediate reading ability, while those with low scores in both tests had the poorest reading ability (6yrs 7mths). This suggests that impairment of both the auditory and the visual domains makes it extremely difficult for a child to learn to read. If impairment is confined to only one domain, the severity of the reading problem is reduced. The small numbers of children failing on only one test make it impossible to

Dunlop Test and Auditory Score

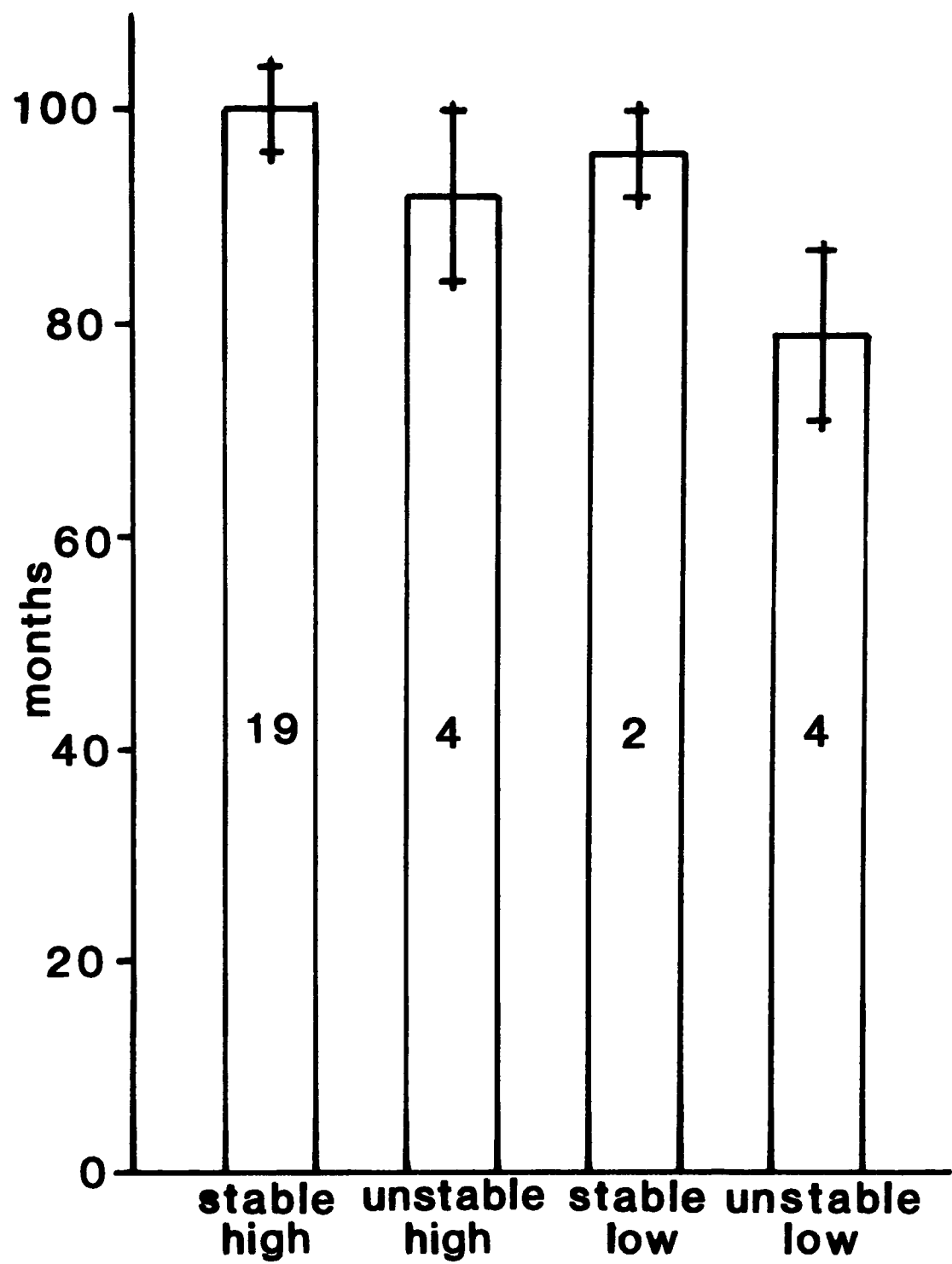


Figure 4.9 - Bar chart showing the reading ability of children grouped according to stability of Dunlop Test responses and score on a rhyming and alliteration task. Children with poor auditory scores and unstable Dunlop Test responses have the poorest reading ability. The number of children in each group is shown. Standard error bars are given.

comment on whether impairment of phonemic segmentation is likely to cause more or less severe difficulties than impairment of visuospatial processing.

4.3.8 - Reading Age Interactions with Vergence Eye Movements

If the reading age deficit found in children with unstable Dunlop Test responses is the result of poor visuospatial representation, it should be possible to find the same sort of interactions in children with unstable vergence eye movement control. Table 4.2 shows the results of the tests described in Table 4.1 arranged according to stability of vergence eye movement control using the criteria set out in the General Methods.

Table 4.2

Test	Stable (n = 24)		Unstable (n = 5)		T	p <
	mean	S.E.	mean	S.E.		
Similarities	61.6	1.30	61.2	2.51	0.14	0.90
Matrices	58.4	1.35	56.6	3.75	0.52	0.60
Auditory	8.96	0.36	7.80	0.73	1.35	0.19
Sequencing	18.4	0.24	17.2	0.92	1.84	0.08
Stereoacuity	23.5	1.22	40.0	12.24	2.81	0.01
Reading Age	8,2	,4	7,2	,6	1.51	0.14
Spelling	8.67	0.36	5.80	1.62	2.72	0.02

Table 4.2 - Scores for seven year old children with stable versus unstable vergence eye movement control.

The pattern of responses for children grouped by eye movement control is different from that found when the same children were grouped by the results of the Dunlop Test. In this case, the spelling

scores of the unstable children were significantly worse than those for the stable children. However, the difference in reading age, although showing the expected trend, failed to reach statistical significance. There was no difference between the IQ scores of the two groups using either the Similarities or the Matrices subtests. There was a trend for children with unstable vergence control to perform poorly on the tests of sequencing. However, this amounted to only one more mistake on average made by the unstable group, and so may not be of significance. Stereoacuity was poorer in the unstable group than in the stable group. The result was more significant when the children were grouped by eye movement control than when the categorisation was made on the basis of the results of the Dunlop Test.

Again, the effects of poor phonemic segmentation and stability of Dunlop Test responses were considered separately. Children were divided into four groups according to their auditory test scores and the stability of their vergence eye movement control. Figure 4.10 shows the results of this analysis. As in Figure 4.9, the children with the highest reading ability were those with stable vergence control and high scores on the auditory test (8yrs 4mths). Children who scored poorly on one of these tests had slightly lower reading ability. The children who showed the lowest reading ability, however, were those who demonstrated both poor phonemic segmentation and unstable vergence control (6yrs 7mths). The numbers in the groups showing some disability were very small, hence this analysis could only show interesting trends. A much larger study might help to confirm these trends, and also help to determine which skill - phonemic segmentation difficulties or instability of vergence eye movement control - gives rise to the most severe reading deficit.

Vergence Control and Auditory Score

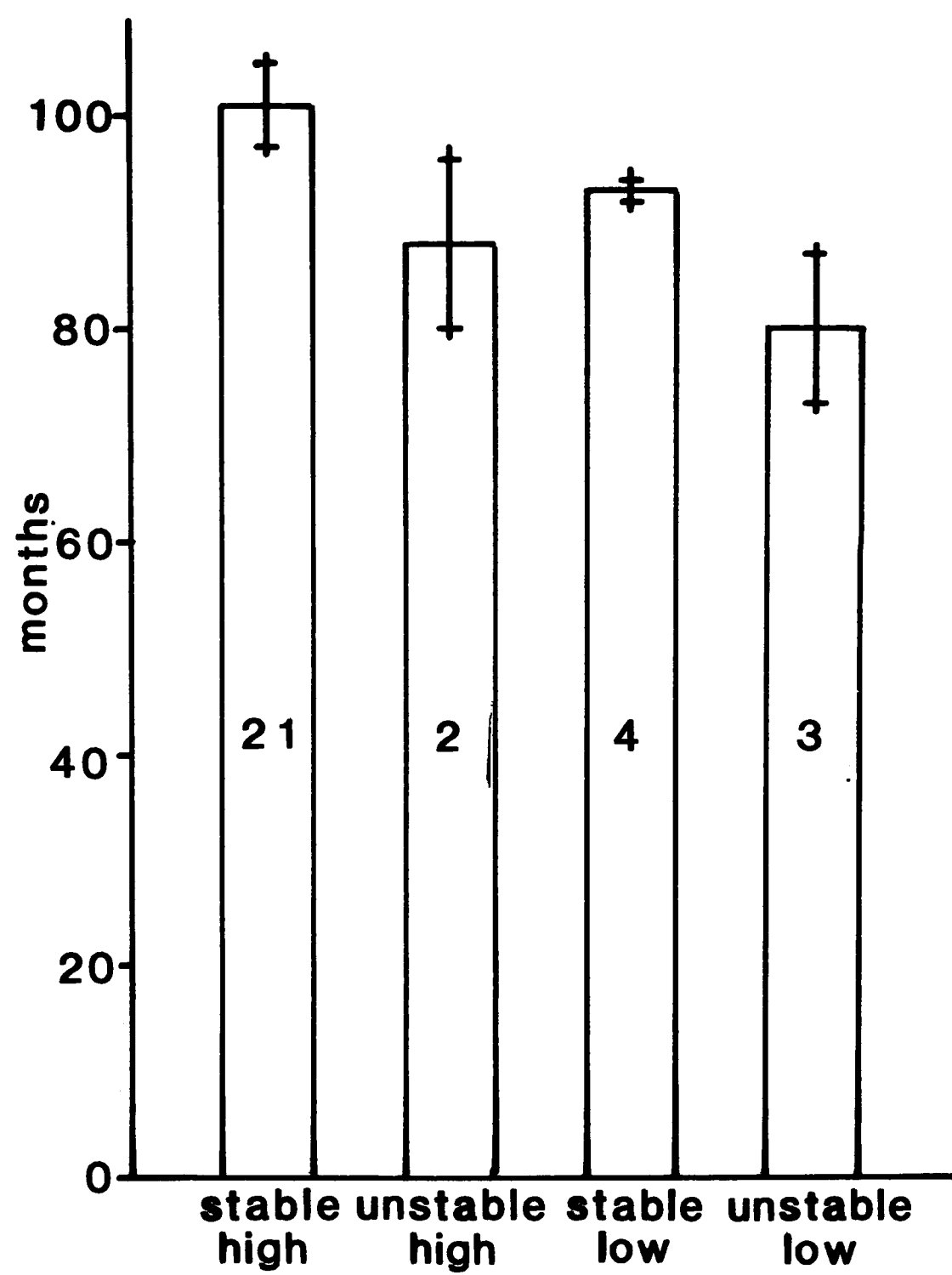


Figure 4.10 - Bar chart showing the reading ability of children grouped according to stability of vergence responses and score on a rhyming and alliteration task. Children with poor auditory scores and unstable vergence responses have the poorest reading ability. The number of children in each group is shown. Standard error bars are given.

4.4 - Discussion

The longitudinal study presented here allowed investigation of the manner in which stable vergence control, stability of Dunlop Test responses, stereoacuity and reading ability develop in a group of unselected primary school children. It showed that the rate of development of stable vergence eye movements was similar to the rate of development of stable responses in the Dunlop Test, and of stereoacuity. This supports the hypothesis that there is a link between the skills needed to perform the Dunlop Test and the control of vergence eye movements. Since stereoacuity also requires accurate control of eye position, the results suggest that some children have a deficit in their ability to control the movements of their eyes accurately when they are required to make disconjugate movements.

The size of the target used to stimulate vergence movements was shown to be an important variable in the size of the movements produced. The larger the target, the larger the vergence movement response. Children with unstable responses in the Dunlop Test were found to make smaller vergence movements in response to all target sizes. This provides further evidence for the theory that failure to control vergence eye movements accurately is the underlying cause of failure to produce stable responses in the Dunlop Test. The greatest proportional difference in the size of eye movements produced between the children with stable and unstable Dunlop Test responses was found with the smallest targets. It seems that the deficit in vergence control is greatest when small targets (1.5 degrees x 1.5 degrees) are used to stimulate the vergence response. This would help to explain why some children find small print more difficult to read than large print. It may be that their vergence control is accurate enough to deal with large targets, but fails when the system is stressed by the

use of small targets.

The stability of Dunlop Test responses and vergence eye movements was shown to correlate with the reading ability of the children. Those with unstable vergence control showed poorer reading ability than their stable counterparts. This cannot be attributed to lack of teaching since all the children were taught by the same teachers. Previous studies examining the correlation between reading ability and vergence control have been unable to control for this variable since the studies involved clinical populations with children from many different educational backgrounds. It is important, therefore that this study has shown that the differences found in the level of reading attained by children with unstable vergence control is not a function of the amount or quality of the reading instruction that they receive.

The results of the Dunlop Test and vergence eye movement control were also found to predict a group of children who had lower reading ability one year after testing. Children with unstable vergence control at 7 years were shown to be poorer readers at 8 years. The reading age of children who developed stable Dunlop Test responses at 6, 7 and 8 years were compared. This showed that the longer the children took to develop stable responses, the poorer their reading ability. However, the children who developed stable Dunlop Test responses by 7 years had shown a marked improvement in their reading ability by 8 years, and were then reading at the same (if not a more advanced) level than the children who had developed stable Dunlop Test responses at younger ages. This would suggest that if a treatment can be found which enables children to develop this stability, treatment might be most effective in young children (up to 7 years old) when it might prevent them from ever developing a severe reading deficit.

When the children were grouped according to their scores on the Dunlop Test, significant differences were found between those with stable responses and those with unstable responses on tests of reading age, stereoacuity and the Matrices sub-test of the BAS. Trends towards differences in spelling and phonemic segmentation were also noted. When the children were grouped according to the stability of their vergence eye movements a slightly different pattern of responses was found. The children with unstable vergence control had significantly lower scores on stereoacuity and spelling. Trends towards lower scores on tests of reading, sequencing and phonemic segmentation were also noted. Since the number of children in the unstable group for categorisation by both the Dunlop Test responses and the stability of vergence control was very small, it is likely that the difference in the profiles seen was artefactual. The trends suggest that children with unstable vergence control, measured by either test perform poorly on tests of reading, spelling, phonemic segmentation and stereoacuity. Studies using larger numbers are required to discover the significance of the differences found in sequencing and Matrices.

The differences found between children with unstable vergence control and those with stable control on tests of phonemic segmentation are interesting. It could be argued that these children were failing to learn to read as a result of their poor phonemic abilities rather than because of their poor vergence control. In order to distinguish between these two hypotheses, the children were divided into groups according to their ability to perform both the auditory and vergence control tasks. This analysis showed that the children with the poorest reading ability were those who showed problems in both the auditory and visual domains. Only these children were found to be falling below their chronological age in reading ability. Since

the rest of the children, even those with problems in either the auditory or the visual sphere alone, were reading above the level expected from their chronological age, this suggests that with appropriate teaching children can be successfully taught to find ways round their deficits. Hence, only children with both auditory and visual deficits need fail to learn to read. The strategies for teaching reading suggested by Bryant and Bradley (1986) use a multisensory approach to reading which stresses the similarities between words in both the visual and the auditory domain. It would seem that children who are taught by methods such as these can use their strengths to learn word reading skills. This highlights the role that educational techniques have to play in dyslexia. It could be argued that fewer children would fail to learn to read if children were found to be at risk by pre-school tests of phonemic and visual processing skills were taught by a multisensory approach tailored to emphasise the child's strengths.

In Figure 4.8 the effects of delay in developing stable vergence control on reading age were demonstrated. The later a child developed stable vergence control, the poorer the eventual reading ability. Very few of the children investigated in this study were found to have reading ages much below their chronological ages: in fact, many of the children were reading well above their educational potential. This is probably a reflection on the excellent techniques used to teach reading in this school. The methods used are multi-sensorial, thus children with only an auditory or a visual problem are still able to learn to read successfully.

Despite this, it could be argued that, if a method of treating children with unstable vergence control was found, then children could be helped to learn to read more successfully if treatment was given

early enough. The results of this study suggest that children who develop stable vergence control by the age of 7 do not fall behind in their reading ability and, in fact, can still become better readers than those who acquire the skill earlier. Stein & Fowler (1985) published the results of a study in which children aged 8 to 12 years were treated by giving occlusion of one eye for all close work. This treatment was found to aid the development of stable responses to the Dunlop Test in twice as many children as would have been expected to gain stable responses developmentally. They also showed an improvement in reading ability after successful treatment. The results of this study have been questioned, however (Bishop, personal communication) and so research is required to authenticate these results. Nevertheless, the search for a treatment for children with learning difficulties attributable, at least in part, to inaccurate vergence control is important. The results of this study suggest that if such a treatment can be found, it might be more effective when used for children below the age of 8.

The results of this cohort study provide evidence for a correlation between vergence eye movement control and reading ability. A developmental trend for stable vergence control was shown to exist whether this control is measured by the responses to the Dunlop Test, recordings of vergence eye movements or stereopsis. Children with unstable vergence control were shown to be poorer readers and spellers than their stable counterparts. However, the poorest reading scores were found in children with both visual and auditory problems. This emphasises how good teaching practice can overcome deficits in one sensory modality, but not in both. It was found that the later children develop stable vergence control, the poorer their reading ability. This suggests that, if a treatment can be found which enables

children to develop stable vergence control, it should be most effective in children below the age of 8 years.

Chapter 5 - General Discussion and Conclusions

In this thesis, evidence has been presented which supports the hypothesis, first advanced by Stein, Fowler and co-workers, that some children fail to learn to read as a result of poor control of their vergence eye movements. The work of Stein and Fowler used a test of visual direction sense - the Dunlop Test - to categorise dyslexic children with poor vergence control. Unfortunately, this test is highly subjective, depending on the co-operation of the subject, and on the experience of the operator. A more objective method for distinguishing children with poor visual direction sense is thus required.

In this thesis, the results of the Dunlop Test were shown to have a high concordance with recordings of vergence eye movements made under the same conditions. This was true for a large clinical group, a group of known dyslexics and a group of unselected primary school children. In the results reported in Chapter 2, categorisation of vergence control was made on the basis of strict, but qualitative, criteria. This procedure again had a subjective component since some children's responses were borderline, and a decision had to be made about which group a given child should belong to. The purpose of this qualitative categorisation was to assess the significance of vergence eye movement recording as a possible indicator of the poor visual direction sense measured in the Dunlop Test. Hence, the high concordance found between these measures gave good grounds for continuing the search for more precise vergence control measures which would differentiate between dyslexics and normal readers.

In the next experiment, two groups were compared on various measures of vergence control. The first was a cohort of 80 children from local primary schools, and the second was a group of 74 confirmed

dyslexics referred to the Orthoptic Department of the Royal Berkshire Hospital for learning difficulties. The two groups were matched for chronological age. Several measures of vergence control were found to be significantly different: the stability of Dunlop Test responses; the amplitude of divergence movements recorded either with the Dunlop Test slides, or with macular fusion slides; and stereoacuity. Hence, there are several measures of vergence control which differentiate between dyslexic and normal readers. A combination of these might be useful diagnostically.

However, using a chronological age match like this does not allow for possible effects of the greater reading experience of the normal readers. It may be that the children who were better readers had acquired a higher degree of vergence control as a result of this increased experience. In order to examine this possibility, it was necessary to employ a reading age match (Bryant & Bradley, 1985). The results of such a match were presented for 20 dyslexics matched for IQ and reading age with younger normal readers. This controls for the effects of reading experience on the measures being tested. The results of the matched paired paradigm showed that, as predicted, the dyslexic children were poorer than the younger normal readers on several measures of vergence control; namely, the stability of Dunlop Test responses and the amplitude of convergence using the Dunlop Test slides. Strong trends ($p < 0.10$) were also found for differences in the amplitude of divergence using macular fusion slides and stereoacuity. When the same comparisons were made for a group of dyslexic children from the clinic compared to matched dyslexics from the school cohort, there were no significant differences in any measures of vergence control. These results support the hypothesis that some dyslexic children fail to learn to read due to impaired

vergence control.

A larger study comparing dyslexics with both reading and chronological age matched children is required in order to assess which measures of vergence control are the most reliable to differentiate normal readers from dyslexics. This is necessary in order to provide clinicians with objective measures of vergence control which can be used to replicate these results in other centres. If the results prove robust, these measures could be used to distinguish a group of dyslexics with poor vergence eye movement control. This categorisation would be useful both educationally to suggest possible teaching strategies and clinically, to devise treatments for the children's eye movement problems .

As a step in this direction, the size of target and rate of convergence demand were varied in an attempt to find the parameters which best distinguished children with stable Dunlop Test responses from those with unstable responses. The magnitude of the convergence movements which a child was able to make before fusion broke was used to investigate the effect of altering of these parameters. Amplitude of fusion was found to increase with increasing target size and decreasing rate of vergence movement. The settings which gave the most significant differences between children with stable as compared with unstable Dunlop Test responses were a target size of 1 degree and a rate of convergence demand of 0.6 degrees/second. These were very similar to the parameters which we have used to test dyslexic children in the Dunlop Test for more than 10 years now.

The results of a longitudinal study of a cohort of primary school children are also presented in Chapter 3. These showed that developmental trends exist for the acquisition of stability of Dunlop Test responses, stability of vergence control and for stereoacuity.

Previous research on the development of vergence control and stereopsis has been limited to infants up to 3 years (Fox, Aslin, Shea & Dumais, 1980, Atkinson & Braddick, 1976). However, the trends found here would suggest that the development of fine vergence control and stereopsis is not completed before 8 years of age and may continue to develop beyond this. A large study in which the development of fine control of vergence, accommodation and stereopsis in children from 3 years to 16 years is measured might help to provide the necessary developmental norms which could then be used to distinguish children who are failing to develop these skills at the normal time.

The fusional amplitude of primary school children with stable Dunlop Test responses was compared with that of children with unstable responses under several different conditions. It was found that children with unstable vergence responses had smaller fusional amplitude than their stable counterparts, particularly when the size of the fusional target used was small, in both divergence and convergence. This provides further evidence in favour of the view that Dunlop Test responses concord with measures of vergence control.

Stereoacuity was also found to be lower in children of all ages with unstable Dunlop Test responses compared with those with stable responses. This difference was greater in the younger children probably since, by 8 years old, most children have reached the ceiling of the test (20 secs of arc).

The expected correlation between Dunlop Test responses and reading ability was also found in this group of primary school children. The reading age of children with stable Dunlop Test responses at 7 years old was compared to their unstable counterparts. This showed that the children with unstable Dunlop Test responses were reading on average one year below the children with stable responses. The reading age of

this unstable group one year later was still lower than that of the stable group, but this trend did not reach statistical significance. The results suggest, however, that the Dunlop Test can be used to predict a group of children with poor reading ability. The predictive use of vergence control measures was further investigated by comparing the reading ages of children as they developed stable responses in the Dunlop test. This showed that the earlier children developed stable Dunlop Test responses, the better their average reading age; thus confirming the predictive ability of the Dunlop Test.

The children investigated in the longitudinal study were given a test in which they had to say words which either rhymed or had the same starting letter as a word orally presented by the examiner. This test is thought to give an indication of the children's ability to segment phonemes. The test also involves finding a word, hence any child with a poor word vocabulary might be disadvantaged, without necessarily having phonemic segmentation difficulties. Bryant and Bradley (1985) overcame this difficulty by presenting four words, three of which rhymed, and asking the child to determine the word which was different. This method was tried, but the children made very few mistakes; so the more difficult task was used. Evidence which suggests that the children were not disadvantaged by word finding in this test comes from their scores on the Similarities sub-test of the BAS. This also tests word finding abilities; but children with low scores on the rhyming task were not found to score lower in this test. When the children's scores on the rhyming task were compared with their responses on the Dunlop Test, it was found that, for the primary school cohort, only children who scored poorly on both tests were significantly retarded in reading ability. This was also true when their stability of vergence control was compared with their scores on

the phonemic segmentation task. The excellent teaching methods used in this school help to explain why very few of these children had a reading deficit. The children were taught using a multisensorial approach. Such teaching appears to allow children with deficits in either auditory or visuomotor processing to bypass these weaknesses, and learn to read through their strengths. This approach to the teaching of reading has been advocated by Bryant and Bradley (1985), who also showed how the analogies between the sounds of words and their letter strings can be used to simplify the process of learning to read. This method of reading by analogy will be of use to children with either auditory or visuomotor impairments since both the similarities in the sounds of the words and in the visual appearances of the words can be stressed.

If some children fail to learn to read as a result of impaired development of vergence eye movement control then this deficit should be apparent in tasks other than reading. If the deficit is only found when reading, it could result from the linguistic problems which are known to affect dyslexic children (e.g. Vellutino, 1985). The first evidence for a perceptual disorder which has no linguistic basis came from comparisons of scores in the Matrices subtest of the British Ability Scales between children with unstable vergence control and those with stable control. The unstable children were found to have significantly lower scores than children with stable responses. This could not be attributed to a difference in overall intelligence between the two groups since the unstable children did not have lower scores on the Similarities subtest which tests verbal IQ. The poor scores on the Matrices sub-test might therefore be attributed to the poor vergence control found in these children. In this task, the children are required to determine the pattern in a 2 x 2 or 3 x 3

matrix. One square is left blank, and the child has to fill in the missing element. This requires the child to scan the small elements which make up the designs in order to determine their pattern. If the child has difficulties in vergence eye movement control, the spatial position of the elements might become confused, leading to mistakes in this test.

This circumstantial evidence is not sufficient proof that the reading difficulties encountered by the group of dyslexic children described here was of a visual perceptive nature. In order to investigate the visuomotor skills of these children in a non-linguistic context, the children were assessed on a test of spatial localisation. The task was designed to determine whether children who showed unstable responses in the Dunlop Test were also poor at localising objects visually, when no linguistic component was involved. This ability was tested in free space, and at the reading distance, since these conditions mimic the reading process more accurately than the viewing conditions of the Dunlop Test. The task used involved a computer game in which the children had to determine the lateral position of a target spot relative to a conditioning spot. The child was asked to simply point in one direction or the other in response, hence there was no linguistic component. This also ensured that the difficulties some dyslexic children are known to have when distinguishing between left and right (e.g. Miles, 1983) did not confuse interpretation of the results.

The children with stable responses in the Dunlop test were compared with children with unstable responses in both a scanning version of the computer game and one in which the target spot appeared at random positions on the computer screen. Both tests showed clearly that children with unstable responses in the Dunlop Test were poorer at

spatial localisation. This supports Ogle's (1962) interpretation of tests, such as the Dunlop Test, which involve apparent movement of monocular targets in a binocular field. He thought that such tests indicate whether subjects employ a stable reference point for the judgement of visual direction.

The results of the localisation task with random target positions also suggested that there was a difference in the spatial processing abilities of males compared with females. Females performed significantly worse than males on this task. This supports previous findings of a male superiority in visuospatial tasks (McGee, 1979). Geschwind and Galaburda (1987) suggested that abnormalities of cerebral lateralisation might result from raised prenatal testosterone levels: they thought these led to reading difficulties as a result of impaired development of the left hemisphere. They postulated that more males are dyslexic since they are subjected to higher testosterone levels in utero than females. The results presented here could be interpreted to suggest that lower than normal levels of testosterone might cause impairment of the right hemisphere. This would lead to poor visuospatial skills, and might be expected to affect females more often than males. This concurs with results reported by Stein and Fowler (1985) that proportionately more female dyslexics than male dyslexics were found to have unstable responses in the Dunlop Test.

The localisation task allowed the investigation of the distribution of errors in the left and right visual fields. It is thought that targets presented to one visual field are processed more rapidly and accurately in the contralateral hemisphere. When all subjects were considered together, no significant differences between the processing abilities of the two hemispheres were apparent. However, when the

children were divided into groups on the basis of their sex and their responses in the Dunlop Test, a significant difference was found between children with stable and unstable responses, in the RLRD task. Specifically, females with unstable Dunlop Test responses made more errors in both visual fields than their stable counterparts, whereas the males made more errors only in the left visual field. It has been suggested that males have more lateralised function than females: hence males are thought to process language functions mainly in the left and visuospatial functions in the right hemisphere, while females show more overlap of function between the hemispheres (Springer and Deutsch, 1985). The results of the random spatial localisation task support this theory since the visuospatial deficit was found in both hemifields in females, but only in the right hemifield, implicating the left hemisphere, in males.

The children were also classified according to the percentage of errors they made in each visual field. Children who made more errors in the right visual field were described as left visual field advantaged (LVFa) and vice versa for greater percentage error in the left visual field (RVFa). The RVFa children showed a higher percentage error rate than the LVFa children on both tasks. This suggests that children who make greater use of their left hemisphere to process a visuospatial task are less efficient at such tasks than those who use their right hemispheres. These results support the hypothesis that the right hemisphere shows superior visuospatial processing abilities to the left.

In conclusion, the evidence presented in this thesis suggests that some children fail to develop stable control of their vergence eye movements at a time when they are required to make accurate assessments of the positions of small visual targets in space. This

failure can be identified through vergence eye movement recordings and measurements of the stability of visual direction sense. It could be argued that the determination of the relative positions of letters in a word does not require the accurate registration of eye movements, but only a comparison of the retinotopic co-ordinates of the letters. However, reading requires frequent changes in the point of fixation, hence eye position has also to be considered. Thus, the spatial co-ordinates of letters within a word must be calculated with respect to a stable map of the visual field. Recent models of the way in which the brain calculates required changes in eye position have been based on egocentric maps which incorporate, not only the retinal co-ordinates of an object, but also the position of the eye in the orbit, the position of the head with respect to the trunk, and the orientation of the body with respect to gravity (Miles & Evarts, 1979). Since, in the experiments described here, the head was stabilised, only the relationship between retinotopic and eye position signals need be considered.

The development of a map of visual space will require calibration of retinotopic co-ordinates with 'outflow' information from the ocularmotor system and proprioceptive 'inflow' information from the eye muscles. Experimental evidence from neurological patients with lesions of the primary visual cortex has shown that, although these patients lose all conscious sense of being able to see and are unable to discriminate form, often they can still determine the position of objects in space (Blythe, Kennard & Ruddock, 1987, Weiskrantz, 1987). This is attributed to the existence of a 'second visual system' which involves subcortical elements (Trevarthen, 1968). This 'second' system incorporates projections from the superior colliculus, via the pulvinar, to secondary visual cortex. The visual system, therefore,

consists of two sub-systems; one dealing with the perception of visual form and the other with localisation of objects in space.

In order to accomplish a higher order task like reading, it is essential to integrate information from both these systems. Husain (1987) suggests that the posterior parietal lobe is involved in this process of integration. Numerous studies have shown that lesions of the posterior parietal lobe result in impairment of the ability to interpret visuospatial information (reviewed in Hécaen, 1985). This impairment can take the form of unilateral spatial neglect, loss of topographical memory, deficits in stereopsis and mislocations. Husain points out that all of these disorders can be explained in terms of a core deficit in the neural representation of space. It seems, therefore, that the posterior parietal lobe may be essential in combining retinal information with proprioceptive information in order to produce a neural representation of visual space. The posterior parietal cortex is anatomically suitable for this function since it receives projections from both the primary visual cortex and from the 'secondary visual system'.

It may be that an impairment in the development of this representation of visual space is the underlying cause of the difficulties the children described in this thesis have in learning to read. A impairment of the neural representation of visual space would lead to difficulties both in determining static visual direction and in producing accurate conscious changes in eye position. Hence, both the poor spatial localisation and the poor vergence control found in these children could be explained by such a deficit. This type of impairment could also explain Pavlidis' (1981b, 1983) findings that some dyslexic children find it difficult to program saccades and maintain fixation even in response to non-linguistic stimuli.

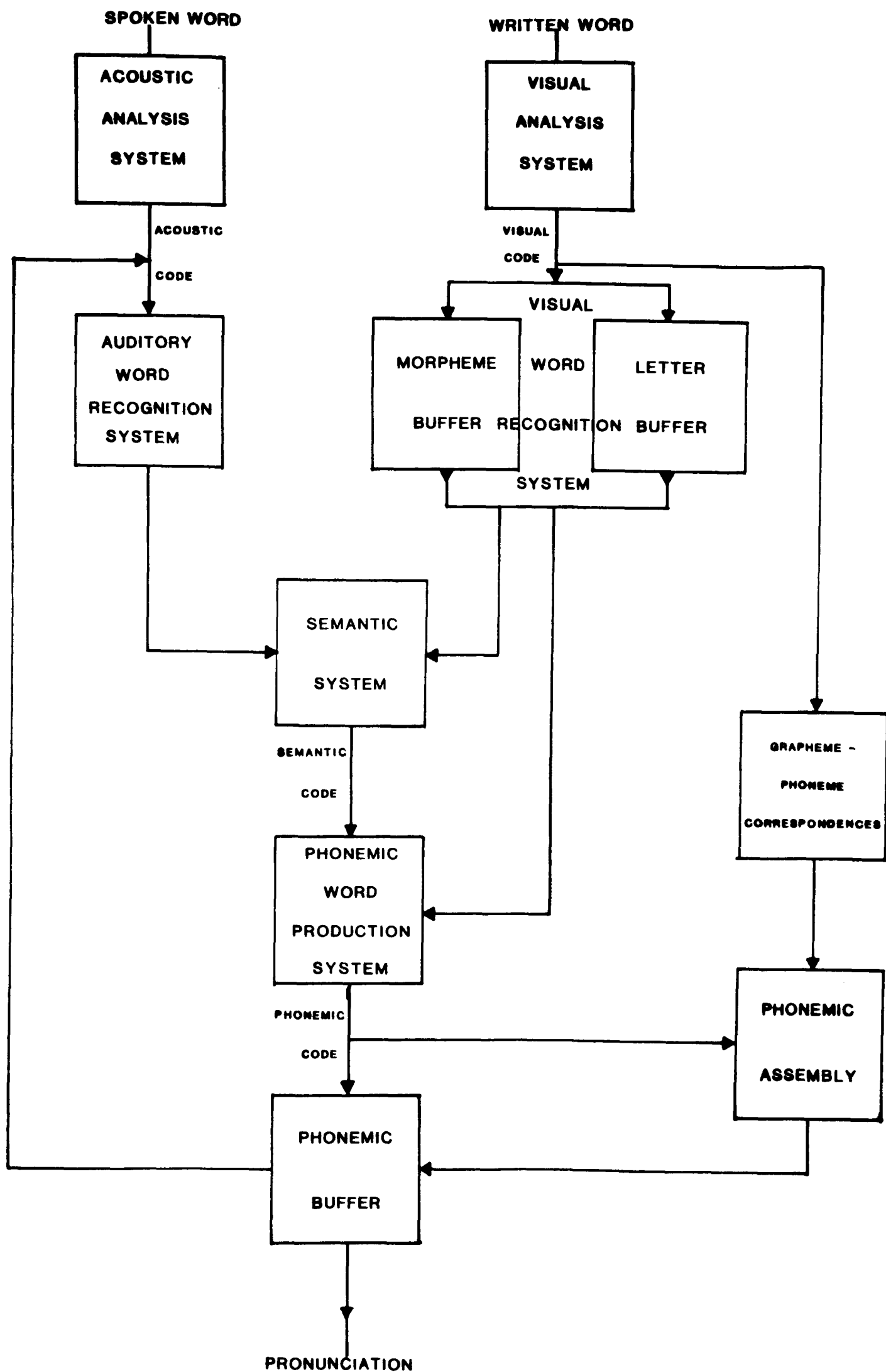


Figure 5.1 - Model of the reading process (from Ellis 1984).

A model for the possible routes from the printed word to understanding adapted from Ellis (1984) is shown in Figure 5.1. There are at least three routes available for the beginning reader when learning to read new words; 1) the child can be taught by the look-and-say method which uses the morpheme buffer of the visual recognition system to view words as wholes. The word is then identified by its overall shape. 2) The child can learn visually by learning the individual letters of the word, using the letter buffer of the visual recognition system. However, neither of these approaches allows the child to decipher new words on his own. 3) The child can be taught the correspondences between letter shapes and their sounds. S/he can then use these to identify new words, so long as the words have a regular phonic structure. This route is shown as the grapheme-phoneme correspondence route. The meaning of the word is accessed via the auditory word recognition system in this case.

Which of these systems will be impaired in the child with vergence control problems? The child with poor vergence control is thought to have difficulty in determining the relative positions of small objects in visual space since s/he has not developed a stable reference point from which to make judgements of visual direction. Hence, any route which involves the accurate spatial sequencing of letters in words will be difficult for such children. This accurate sequencing is vital to the process of grapheme to phoneme translation and would also be used in the letter buffer of the visual recognition route. Hence, these children will only be able to learn to read through the morpheme buffer of the visual recognition system.

Frith (1985) described a developmental model for the process of learning to read. She suggested that four phases of reading development could be distinguished. In the first phase, the symbolic

phase, the child learns that text can be used to give meaning. This is followed quickly by the logographic phase in which the child learns to identify common words, first by outstanding features like the starting letter, and then more accurately by their approximate visual appearance. The next phase of reading development is the alphabetic phase. At this time, children learn to make associations between letter shapes and their sounds. This begins when the child starts to learn to spell. The approximate visual recall acquired in the logographic phase is then found to be insufficient to reproduce correct spellings. The skill of grapheme-phoneme correspondences can be applied to the reading process soon after the child begins to use this skill in spelling. In the final stage of reading development, the child learns to apply all the skills so far acquired, along with contextual cues, to achieve fluent reading.

Children with poor vergence control are likely to have difficulty when transferring between the logographic and alphabetic phase of reading development. Such children will be able to see the approximate positions of letters in words, so they should be able to read some sight words. They, therefore, form a different group to the dyseidectic dyslexic children described by Boder (1973) who could not read any sight words. Unfortunately, children with phonemic segmentation problems are likely to be arrested at the same phase of the developmental process as children with poor vergence control. This means that testing the errors that children make when reading and spelling will be insufficient to distinguish between the two groups. It will be necessary to incorporate tests which assess skills other than reading into the battery of tests used to determine the nature of the dyslexic problem. Tasks involving phonemic segmentation which use an oral presentation will help to distinguish children with poor

auditory skills. In the same way, tasks which involve spatial processing of small objects other than text might prove to be diagnostic of visuospatial difficulties.

Thus, the evidence presented in this thesis suggests that some children fail to learn to read as the result of a deficiency in their vergence eye movement control. This was shown by comparing dyslexic children with both chronological and reading age matched controls in a series of tests designed to assess their vergence eye movement control. The possibility that the children performed poorly on the visuomotor tasks as a result of poor linguistic ability was considered. Evidence was presented which showed that the children with unstable vergence control also performed poorly on a test of spatial localisation which had no linguistic component. Thus, some dyslexic children could be demonstrated to have problems with the localisation of non-linguistic targets in visual space. This impairment is thought to be detrimental when learning to read, adding to any linguistic difficulties which might impede the child's progress.

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