Early Cognitive Neuropsychological Profiles and Development of Reading Skills

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~Declaration~

This thesis is based on research undertaken solely by the author who assumes all responsibility for its contents. The research reported in **Chapters 6, 7** and **8** has been presented previously in the form of papers and posters at national British Psychological Society and Psychophyiological Society conferences, at the Third International Conference of the British Dyslexia Association and as invited addresses to the North Warwickshire Dyslexia Association and to the Warwickshire Specific Learning Difficulties Support Services. Papers have also been presented at the International Congress of Psychophysiology's Annual conference in Thessaloniki, Greece and at the Izaak Walton Killam Hospital for Children, Halifax, Nova Scotia, Canada. Abstracts from these conferences have been published in the *Proceedings of the British Psychological Society*, in the *Journal of Psychophysiology* and in the *International Journal of Psychophysiology.* The work reported in **Chapter 7** has also been published as a paper in the *International Journal of Psychophysiology.*

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~Abstract~

The present thesis sought to investigate the precise relationship between the cognitive and psychophysiological profiles of developing readers, of established readers and of failed readers. Phonological processing tasks and visuospatial tasks were used to assess relevant auditory and visual cognitive skills; handedness and EEG measures were used to provide indices of cortical organisation and activation.

A 21/2 year longitudinal investigation of some 150 pre-readers provided evidence of mutually facilitative relationships between and within specific types of phonological skill and phonological memory. Early significance of visual skills was subsequently superseded by the importance of these phonological skills. The acquisition of early reading skills was associated with a shift towards increased dextrality as measured by hand skill and hand preference; this relationship was not evident in subsequent stages.

Cross-sectional studies comparing dyslexic children with chronological- and reading-age matched controls extended these findings. The dyslexic readers displayed impaired phonological processing and phonological memory skills relative to chronological-age matched competent readers; similarities were observed between dyslexics and reading-age matched controls. Visual perceptual skills failed to differentiate between the chronological-age matched competent and impaired readers, although both out-performed younger control readers. ERP measures consistently demonstrated diffuse patterns of bilateral activation in dyslexic readers as opposed to asymmetric activity lateralised to the left hemisphere in control readers. Between group comparisons of *inter*-hemispheric activity revealed greater levels of right-hemisphere involvement in the dyslexic samples; between group comparisons of *intra*-hemispheric activity revealed evidence of greater involvement of fronto-central regions in the dyslexic samples.

It is proposed that these data provide supportive evidence for the central involvement of phonological processing skills in the development of reading, underpinned by the normal development of asymmetric patterns of cortical lateralisation. Children where this development is delayed or deficient will display the reading difficulties characteristic of developmental dyslexia.

The greatest thing in the world

A

is the alphabet

B

as all wisdom is contained therein ~ except

C

the understanding of putting it together

(After Massaro, Taylor, Venezky, Jastrzembski & Lucas, 1980)

~ CHAPTER 1 ~

Reading, cognitive neuropsychology and dyslexia: An Introduction

"...to completely analyze what we do when we read would be the acme of a psychologist's achievements, for it would be to describe very many of the most intricate workings of the human mind, as well as to unravel the tangled story of the most remarkable specific performance that civilisation has learned in all its history"

Edmund Burke Huey (1908, p. 6)

1.1 Introduction:

Investigations of the processes underlying reading date back almost a century and, as Huey's remark implies, have consistently attracted a great deal of psychological interest (Bryant & Goswami, 1987; Cossu, Rossini & Marshall, 1993). Of particular interest is the reading ability of children, in whom literacy skills are developing, in the hope that it may be possible to elucidate the most elemental mechanisms which allow reading to occur.

Research into the mechanisms underlying the reading process in children has generally followed three empirical routes. One approach examines the initial acquisition of literacy skills in young children, another the cognitive profiles of established, competent readers, and yet another children who fail to acquire age-appropriate reading skills in the absence of overt intellectual or neurological deficits (i.e. developmental dyslexics: Kamhi, 1992; Galaburda, 1994). Of course, this is not to deny the existence of a vast wealth of literature concerned with the mechanisms underlying acquired dyslexia (the descriptive label for individuals whose previously normal reading skills are impaired by accident or disease;

see Ellis, 1984; Seymour, 1987). This distinction between the two types of dyslexia is important. Whereas acquired dyslexics lose *successfully learned* reading skills as a result of cerebral damage, developmental dyslexics experience specific difficulties in *learning* to read. An investigation of the process whereby children *fail* to learn to read as expected may provide an insight into the cognitive and neuropsychological environment necessary for the *successful* acquisition of reading skills. The theoretical importance of this insight for understanding successful and impaired reading, and its practical importance for predicting reading success or failure, are significant (these issues are discussed below). Such an investigation forms a fundamental part of the present thesis.

Reading is complicated by not being a unitary phenomenon. The mechanisms involved in its development and operation, together with the factors which may affect the successful course of this development, may be cognitive, behavioural or biological. These three levels have been incorporated into a theoretical framework which explains the integration of factors involved in the reading process (see **Section 4.5**; also Frith, 1995). The measures employed in the present thesis (see **Chapters 6**, **7** and **8**) addressed each of these levels in an attempt to explore the various cognitive, behavioural and neuropsychological factors which might contribute to the development of reading over time, both in children with normal reading skills and in children with reading difficulties (developmental dyslexics). Thus, these studies are theoretically important, in relating observed, behavioural differences to variations in hemispheric lateralisation via differences in cognitive ability.

As reviewed in **Chapter 2,** it has been suggested that the primary mechanisms involved in normal reading are: phonological processing skill (Wagner & Torgesen, 1987; Torgesen, Wagner & Rashotte, 1994), short-term memory (Jorm, Share, MacLean & Matthews, 1986; Ford & Silber, 1994) and, to a lesser extent, visual processing skills (Bigelow & McKenzie, 1985; Eden, Stein & Wood, 1993). Results have variously been interpreted as indicating that competence in these individual cognitive skills is a necessary *pre-cursor* to reading (Ellis & Large, 1987), that is it a *product* of increasing literacy skills (Perfetti, Beck, Bell & Hughes, 1987; Morais, Alegria & Content, 1987) or that the relationships between the measures are 'mutually supportive' (Stanovich, Cunningham & Cramer, 1984; Share, 1995).

The inconsistency of these findings may be explained by methodological irregularities between studies. For example, numerous studies have investigated the contributing roles played by *different* aspects of *different* cognitive abilities in the acquisition of reading skills. Researchers interested in the relationship between phonological processing skills and reading have employed various measures including syllable and phoneme segmentation, sound blending, rhyme awareness, rhyme production and phoneme deletion (see **Section 2.3**; also Muter, 1994). In that different measures may be differentially related to the cognitive skills underlying reading, the diversity of findings is unsurprising. Furthermore, these studies are generally cross-sectional in design or, if longitudinal, include a couple of testing sessions over a relatively short period relative to the child's reading development (see **Section 6.1.5.**). Interest in the inter-relationships between the cognitive abilities involved in reading, and in the possible direction of causality between these abilities and the developing reading skills, however, *demands* the adoption of a longitudinal approach. Each of these components should be monitored, in parallel, at regular stages across the period of acquisition of early reading skills. No study to date has undertaken to examine the different facets of a child's cognitive armoury in an integrated investigation spanning the years of early reading acquisition. This was one of the aims of the longitudinal study reported in **Chapter 6**.

On the basis of the evidence discussed in **Chapters 2** and **6** it is expected that any relationship which exists between visual perceptual skills and reading ability will only be apparent, if at all, in the early stages of reading development. Measures of phonological processing ability and phonological memory, however, are predicted to demonstrate a more far-reaching relationship with emergent reading skills. These measures are expected to correlate with reading ability across the course of the investigation, although the precise nature and direction of these relationships remains to be elucidated.

The studies reported in **Chapters 7** and **8** extend and complement the significance of the longitudinal study by assessing cognitive ability in children with established literary competence and in children who have failed to acquire age-appropriate reading skills. It is expected that the abilities which are necessary to sustain normal reading development in the early stages will also differentiate between competent readers and developmental dyslexics at a later stage. As mentioned previously, it is assumed that an investigation of the problems of children who *fail* to acquire normal reading skills will contribute to our understanding of *successful* reading. A study of the cognitive and psychophysiological behaviour of children with developmental dyslexia should help, therefore, to contribute towards our understanding of reading ability.

As noted above, the term 'developmental dyslexia' generally relates to individuals who display a specific impairment in the acquisition of age-appropriate reading skills in the absence of intellectual or neurological deficits (Stanovich, Nathan & Vala-Rosi, 1986; Pavlidis, 1990). The precise definition of developmental dyslexia is fraught with controversy, however, as discussed in **Section 3.1.** Early theories of developmental dyslexia focused on the notion of visual and auditory perceptual deficits. Hinshelwood (1895), for example, wrote of "word blindness", Morgan (1896) of "mind blindness" and Orton (1928) of "strephosymbolia" (the twisting, or reversal, of symbols). Although a minority of dyslexic children *may* suffer reading impairments resulting from purely auditory or visual perceptual problems (Seymour, 1986; Johnston, Anderson, Perret & Holligan, 1990; Goulandris & Snowling, 1991), the majority of developmental dyslexics tend to have normal vision and hearing (Morrison, Giordani & Nagy, 1977). Subsequent research into the aetiology of dyslexia in otherwise normal children has focused on the cognitive processing abilities of these children (as detailed in **Chapter 3**). This has exposed a core of specific deficits, generally involving some aspect of auditory phonological processing such as rhyme awareness, phoneme manipulation and the retention of information in phonological memory (Bradley & Bryant, 1985; Cataldo & Ellis, 1990; Snowling, 1991). Thus, the crucial role played by these individual skills in the normal acquisition of reading would appear to be supported, although the precise interaction of the different measures, and the relative contribution of each at different stages of normal and abnormal reading development has yet to be determined.

At this stage, note must be taken of Beaumont's (1982) admonition, that, "A psychology without any reference to physiology can hardly be complete. The operation of the brain is relevant to human conduct, and the understanding of how the brain relates to behaviour may make a significant contribution to understanding how ... psychological factors operate in directing behaviour" (Beaumont, 1982, p. 4). In fact, attempts to relate different aspects of linguistic processing with underlying physiology have a long history, although traditionally these investigations were driven by the study of individuals whose language processing skills had been impaired or lost as a result of accident or disease (see, for example, Broca, 1861; Dax, 1865; Wernicke, 1874). Over the years, however, the development of increasingly sophisticated techniques has facilitated investigation of the relationship between psychology and physiology in normal, intact subjects (see **Section 4.1** for discussion). Such studies have generally implicated regions of the left cerebral hemisphere of normal adults in the processing of auditorily and visually presented language (Price, Wise, Watson, Patterson, Howard & Frackowiak, 1994; Segalowitz & Berge, 1995). Yet, in spite of these methodological advances, the precise relationship between brain (at the biological level of Frith's (1995) model) and behaviour remains something of a mystery.

Of particular relevance to the present thesis is the observation that relatively little is known about the neuropsychology of reading development in normal children. Cross-sectional studies of normal subjects of different ages have attempted to chart the development of handedness (Kilshaw & Annett, 1983), and to relate differences in handedness to differential linguistic and non-linguistic abilities (McKeever, 1991; Annett, 1992b), but no attempt has been made to relate longitudinal changes in handedness to increasing reading skill in children. In view of this paucity of neuropsychological research, one specific aim of the longitudinal study reported in **Chapter 6** was to explore the relationship between cognitive ability and cerebral lateralisation, and to investigate its stability, in a group of children as they learn to read. Measures of handedness (hand preference and hand skill) were employed at each testing stage for this purpose (Annett, 1970). To the extent that measures of hand preference and hand skill may be taken to reflect underlying cortical lateralisation, it is expected that any changes in lateralisation which occur with the acquisition and development of preliminary reading skills will be reflected in the handedness measures (see **Chapter 4**).

While little is known about the neuropsychology of *normal* reading development, evidence points towards a relationship between cognitive processing deficits and anomalous cerebral lateralisation in dyslexics. This evidence derives from three sources: behavioural measures, where reduced linguistic competence is interpreted as reflecting deviation from the normal development of left hemisphere superiority for the processing of linguistic information (Larsen, Hoien, Lundberg & Odegaard, 1990; Annett, 1992b; Galaburda, Menard & Rosen, 1994); indirect measures of cerebral lateralisation, where dyslexic samples are reported to display patterns of atypical handedness and attenuated or reversed perceptual advantages on divided visual field and dichotic listening tasks (Obrzut, Obrzut, Bryden & Bartels, 1985; Broman, Rudel, Helfgott & Krieger, 1986; Annett & Manning, 1990b); and neural imaging studies which have provided more direct evidence of reduced or delayed left hemisphere specialisation for the processing of language in dyslexic samples (Voeller, Armus & Alhambra, 1983; Larsen *et al*, 1990; Galaburda *et al*, 1994). As discussed in **Chapter 4**, however, evidence of the precise nature of the relationship between reading ability and cortical lateralisation, as revealed by these various measures, is generally inconclusive. This relationship is addressed by the studies reported in **Chapters 7** and **8**.

Specifically, the primary aim of the studies reported in **Chapter 7** was to examine the relationship between individual differences in perceptual asymmetry (as indexed by a verbal dichotic listening task) and event-related potential (ERP) measures of sensory asymmetry in competent and impaired readers. The recording of ERPs, with the focus on the early components of the waveform (the N100 and the P200), allows the investigation of the sensory aspects of linguistic processing and of the allocation of attentional resources (see **Section 4.4.5**). If real differences exist between normal and impaired readers, possibly with a neurophysiological basis, these psychophysiological techniques might provide data to highlight such differences. A further aim of these studies was to determine the extent to which these differences are reflected in simple measures of hand skill and hand preference in developmental dyslexics and in samples of chronological-age and reading-age matched competent readers.

The final cross-sectional study (**Chapter 8**) was designed to explore any psychophysiological differences between normal readers and dyslexic children during cognitive processing. This study employed a phonological oddball task, again with contemporaneous recording of ERPs; the focus of this study was the P300, a positive going component of the ERP thought to reflect cognitive processing (see **Section 4.4.7**). Thus, the intention was to investigate the extent to which phonological processing is reflected in lateralised electrophysiological activation in children of normal reading ability (chronological-age and reading-age control children) and in children with developmental dyslexia.

Underlying these latter studies (reported in **Chapters 7** and **8**) was the prediction that the psychophysiological measures would combine to present a profile of reduced cerebral asymmetry in the dyslexic children, relative to the chronological-age control readers. A comparison of the psychophysiological profiles of the reading-age matched dyslexics and control children enabled an investigation of the origin of any cortical anomalies associated with dyslexia. Similarities in the degree of asymmetry between the children matched for reading ability would indicate that the reading and cognitive processing problems experienced by the dyslexics *may* be due to a *delay* in their psychophysiological development; if the dyslexics proved less lateralised than the reading-age controls, however, it may be suggested that their problems reflect a more fundamental *deficit* at the psychophysiological level.

Before these experimental chapters, **Chapters 2-4** introduce and critically review topics that are important and relevant to the data presented and discussed in **Chapters 6-8**. Current knowledge of the cognitive correlates of normal reading is discussed in **Chapter 2** where contemporary models of the stages of initial reading acquisition are introduced and evaluated. **Chapter 3** extends this discussion to include research into the failure of some children to follow the expected progression towards the development of fluent reading skills, i.e., it focuses on the reading development of developmental dyslexics. The importance of psychophysiological factors is discussed in **Chapter 4**. This chapter will provide an evaluation of the neuropsychological evidence regarding cerebral lateralisation in normal and abnormal reading development, together with a review and discussion of the psychophysiological techniques used in reading research.

Longitudinal and cross-sectional studies, as noted above, appear in **Chapters 6, 7 and 8.** **Chapter 9** draws together the findings from these studies and attempts to interpret them in terms of the current models of reading development. Frith's (1995) model is also invoked to provide a conceptual framework within which to discuss the observed relationships between the cognitive and neuropsychological profiles of children at different stages of literary competence and in children with developmental dyslexia.

~ CHAPTER 2 ~

The psychology of reading

"The areas of knowledge and ignorance in the scientific study of reading are ... skilled reading and the process of becoming a skilled reader. What we know a lot about is skilled word recognition... What we still know much less about are the processes of word recognition that serve a child as he or she learns how to read"

Perfetti, 1992, pp. 145-146.

2.1 Introduction:

As noted in **Chapter 1**, the present thesis is concerned primarily with the developmental process whereby children *acquire* early reading skills, or *fail to acquire* these skills. The ensuing sections will focus, therefore, on the mechanisms underlying word recognition at different stages of early reading development. This will serve as an initial step in the current attempt to redress the imbalance in knowledge of the processes underlying reading in the skilled reader and in the novice, observed by Perfetti.

2.2 Models of normal reading development

By the age of 4-5 years a normally developing child already has hundreds of words stored in its 'auditory word recognition' and 'phonemic word production' systems (Ellis, 1984); it also has a rudimentary understanding of grammar, syntax and semantics. The child at this stage of development only lacks those linguistic aspects specifically associated with reading and writing, such as letter/ word recognition and knowledge of grapheme-phoneme correspondences (Ellis, 1984). In an attempt to explain how these skills are developed and integrated with existing abilities, a number of models of reading acquisition have been proposed. The general basis of these models is the suggestion that literacy develops in a sequence of stages, each of which must be passed before progression to the next. The most influential of these models are considered below.

2.2.1 The Cognitive Developmental model

This model suggests a four-stage account of the linguistic processes and decoding strategies involved in learning to read (Marsh, Friedman, Welch & Desberg, 1981), and appears to serve as the basis for other descriptive models of reading development (Seymour & MacGregor, 1984; Frith, 1985).

The first stage of Marsh *et al*'s model is characterised by 'linguistic guessing'. At this stage, a child learns to recognise a few words - such as "and" or "the" - from their visual appearance (according to salient features of the word) without any reliance on alphabetic or phonemic knowledge. If an unfamiliar word is encountered in a sentence the child will guess at the word on the basis of its context, selecting from words stored in its phonemic word production system, although the guessed word is likely to bear no visual resemblance to the actual word; unfamiliar words presented out of context will not be read. Phonology plays no part in this initial stage of word recognition.

The second stage of reading development, entered in the first year of reading, is that of 'discrimination net guessing', in which context is increasingly used to supplement linguistic cues in word identification. During this stage, the child's visual word recognition system is expanding. If shown an unfamiliar word in isolation the child will guess at a known word with some visual similarity (with the same first or last letters, for example) to the new word. The drawing of rudimentary analogies enters the child's literary repertoire, such that the word "window" might be read as "wing", or "running" as "ring". Children at this stage are able to read familiar words, but their lack of phonic skills makes them unable to apply grapheme-phoneme conversion rules in reading unfamiliar words.

By the age of seven, this model asserts, most children start to become familiar with simple grapheme-phoneme correspondence rules in the 'sequential stage' of reading development, as they learn to recognise that the same patterns of letters appear in different words with shared sounds. The child will start to "sound out" words, although for the first time in the child's reading development this process may produce non-words and regularisation errors. The word 'watch', for example, may be pronounced to rhyme with 'catch' (Frith, 1985). Words are decoded grapheme by grapheme, although exactly how young children break words down into their constituent graphemes, instead of attempting to read letter by letter, has yet to be explained (Stuart & Coltheart, 1988). As words are decoded they enter the child's visual word recognition system. Thus, familiarity with words reduces the need for decoding in the future, although phonological decoding remains an option, especially when the child is confronted by novel words. During this stage of reading development phonological awareness is of vital importance to the reader.

Once the child reaches the fourth, 'hierarchical decoding', stage of development its phonological decoding ability has developed into a sophisticated technique, including greater use of phonological analogies (reading the unfamiliar word 'bin' by analogy with the familiar word 'pin', for example) and recourse to conditional rules of pronunciation (such that the letter c is pronounced /k/ when followed by the letters a, o or u, but as /s/ when succeeded by an i, e or y).

This model appears to possess surface validity in that it is sufficiently able to account for the pre-eminence of visual strategies in the initial stages of literacy acquisition and the increasing use of grapheme-phoneme correspondences and analogies at later stages of development (as discussed later). It also has its limitations, however, in that it takes no account of the influence of the pre-literate child's rudimentary phonological awareness on subsequent reading development (the importance of rhyme awareness in the pre-literate child is discussed in **Section 2.3**); neither does it consider phonological units larger than the phoneme in its conceptualisation of phonological codes, thus ignoring the utility of larger units (onsets and rimes) in the drawing of analogies (see Goswami, 1988, 1990). The model has also been criticised as being too vague to be conceptually viable (Goswami & Bryant, 1990).

2.2.2 Frith's Three Stage model of reading development

A modification of the cognitive developmental model suggests that the acquisition of reading may be viewed as progressing through three stages (Frith, 1985). The first two stages, involving the use of logographic and alphabetic reading strategies, are viewed as essentially equivalent to Marsh *et al*'s linguistic guessing, discrimination net guessing and sequential decoding stages. Once again the beginning reader is conceptualised as developing from an initial stage in which words are recognised purely on the basis of their visual form to a stage where the child embraces elementary grapheme-phoneme decoding in addition to the visual recognition of word forms of stage 1. It is the third, orthographic, stage which discriminates between the two models. Frith envisages this stage as involving not only logographic and alphabetic strategies but also the analysis of words into orthographic units larger than the phoneme, possibly at the level of the morpheme (the smallest meaningful unit within a word). These units can be re-combined into "an almost unlimited number of words" (Frith, 1985, p. 306). This stage differs from the logographic stage in that it is "analytic in a systematic way and... non-visual"; it differs from the alphabetic stage by dealing with larger functional units and by being essentially "non-phonological" (Frith, 1985, p. 306).

However, Frith's argument that the recognition of orthographic units depends on a non-phonological process is debatable as the conversion of orthographic units, such as "ight", into their corresponding sound representations is necessarily phonological (Goswami & Bryant, 1990). Furthermore, the suggestion that children only learn to recognise words on the basis of spelling sequences at a fairly advanced stage of reading development is in contrast to evidence that young children, with even fairly rudimentary reading skills, are able to analogise from known to unknown words with shared letter sequences (Marsh *et al*, 1981; Goswami, 1986, 1988). Thus the model takes no account of the pre-literate child's existing phonological skills and their potential influence on the acquisition of literacy (Goswami & Bryant, 1990).

An additional criticism of the foregoing models is their rigid adherence to the concept that children learn to read by progressing through a series of discrete stages. A precise definition of boundaries between stages is difficult to obtain and there is a general failure to take account of individual differences in the abilities of children and teachers. It may be more prudent, therefore, as Beech (1987) suggests, to consider the acquisition of reading as a succession of overlapping processes rather than a sequence of identifiable stages, thus allowing for individual variation. This approach, adopted by Goswami and Bryant (1990), considers qualitative differences between the rates of reading development of individual children, as reviewed below.

2.2.3 Goswami & Bryant's Theory about Causes

Goswami and Bryant's (1990) theory attempts to characterise factors involved in the progression from pre-literacy to early reading competence. The first of these factors is pre-school phonological (rhyme and alliterative) awareness. Important at this stage of development is the ability to discern onset (the initial consonant cluster) and rime (the first vowel and succeeding consonants) and to use these to categorise words. Children who are sensitive to rhyme prior to the onset of literacy instruction are thought to be able to utilise this awareness to categorise words on the basis of the onset and rime; when they come to read these children realise that words that share common onsets or rimes also generally share letter sequences. It is this realisation which facilitates the reading and spelling of unknown words by analogy to known words (Goswami, 1986, 1988). It is suggested that children are able to draw analogies from the earliest stages of reading acquisition, but that the sophistication and accuracy of these analogies develops with reading experience (Goswami & Bryant, 1990).

The second factor considered by this model is a child's increasing familiarity with an alphabetic script; this is considered to bring about a rapid awareness of phonemes (as discussed in the next section). There is thought to be some delay before children apply this new-found awareness to enhance their literacy development, however, as noted below, although it is reported to be evident in their spelling strategies.

The third factor is the reciprocal relationship between a child's reading and spelling abilities. This relationship, it is argued, undergoes a qualitative change over time. Initially the facilitatory effect of phonological awareness is restricted to spelling skills, but after approximately two years' reading instruction the child is considered to be able to use spelling strategies to aid reading. Although the model is still rather speculative, current evidence does support such a position.

It is clear from the above brief review of reading models that the ability to read does not exist in isolation from the development of the child's cognitive repertoire. Different cognitive skills appear to be of critical importance at different stages of reading development and may account not only for variations in the *rate* of reading development but also in the *success* of a child's reading development. Of key importance in the acquisition of reading are the three cognitive components which will be considered in some detail in the next chapter: phonological processing, verbal memory capacity and visual perception.

2.3 Cognitive correlates of reading I: phonological awareness

According to Bryant & Goswami (1987), "the discovery of a strong relationship between children's phonological awareness and their progress in learning to read is one of the great successes of modern psychology" (p. 439). Although few would argue with this sentiment, the precise nature of this relationship is not exactly unambiguous.

It has been argued that when confronted by an unfamiliar word, a child must be able to sub-divide the word into letters or units of letters which correspond to spoken sounds and then reassemble these sounds into a recognisable word (Wagner & Torgesen, 1987). This description of the process of grapheme-phoneme conversion may be overly-simplistic. Liberman (1973), for example, observed that a child attempting to read the previously unseen word "bat" on the basis of its letter-to-sound correspondences would produce the nonsense word "buhatuh". The relationship between phonemes and the sound of a word is considered to be that of " a very complex code, not a simple, one-to-one substitution cipher" (Liberman, 1973). More recently, Adams (1990) has noted that reading by simply knowing the sounds of individual letters is similar to travelling a journey from looking at the map. While the former undoubtedly benefits from the latter it is not quite as straightforward a result as may be expected.

2.3.1. What is phonological awareness?

A great deal of uncertainty surrounds the precise definition of the term "phonological awareness" (Adams, 1990; Stahl & Murray, 1994). At a surface level, it refers to an appreciation of the individual sounds within words (including syllables and phonemes) and also to the understanding that words can be broken down on the basis of these constituent sounds (Muter, 1994). More specifically, it is suggested that it is a construct with numerous facets, as assessed, for example by measures of syllable or phoneme segmentation, manipulation, sound blending and rhyme awareness (Adams, 1990).

There are degrees of inter-correlation between different aspects of phonological awareness. Stanovich *et al,* (1984), for example, report high inter-correlations between all of the non-rhyming measures included in their test battery (including initial and final phoneme deletion, tests of alliteration, initial consonant transposition and identification of initial consonants); furthermore, all of these non- rhyming measures were found to load highly on a single factor (accounting for 47.8% of total variance) and significant correlations were found with later reading ability. From this Stanovich *et al* concluded that these measures were indeed tapping the same construct. A similar result is reported by Wagner & Torgesen (1987) who performed a factor analysis on the data of Lundberg, Olofsson & Wall (1980; see **Section 2.3.2 (a)**). On the basis of their findings they report that "much of the variance in common measures of phonological awareness can be accounted for by a single latent ability" (p. 199).

To investigate the possible influence of general cognitive ability and reading competence on phonological awareness, Wagner & Torgesen (1987) partialled the effects of these variables from Lundberg *et al*'s (1980) data. They found that kindergarten phonological awareness remained strongly predictive of first grade reading ability independent of general cognitive ability; when kindergarten reading measures were partialled from the data, however, only two of the nine correlations remained significant. Thus, Wagner & Torgesen conclude that differences between the children in terms of kindergarten reading skill may account for the observed correlations between kindergarten phonological awareness and first grade reading. The causal implications of these data are ambiguous.

Using a similar phonological awareness test battery Yopp (1988) obtained 2 principal factors, the first encompassing phoneme blending, segmentation, counting and isolation, the second phoneme deletion. Further analysis revealed these two factors to be highly correlated, however, thus introducing the possibility that they reflect two levels of difficulty rather than two different kinds of phonological skill. The simpler tasks of the first factor required only one cognitive operation - the blending, segmentation, counting or isolation of a constituent sound; the phoneme deletion task of the second factor involved two cognitive operations for its completion - isolating the specified phoneme and holding the remaining sound in memory while deleting it from the stimulus word.

This second factor was thought to reflect "compound phonemic awareness", the first "simple phonemic awareness".

Rhyming ability was found to be only minimally implicated in these two factors, suggesting that rhyme tasks may tap a different phonological ability to those assessed by other tests of phonemic awareness (Yopp, 1988). This finding prompted Yopp to caution against using measures of rhyming ability to draw inferences about the relationship between phonological awareness and reading ability. This view is not widely shared, however. Goswami & Bryant (1990), for example, argue that whereas segmentation, deletion and transposition tasks are measures of phonemic awareness, rhyming tasks assess an individual's sensitivity to onset-rime units within words. According to this view tests of phonemic awareness relate to the phonemic structure of the word ("cat" -> /c/, /a/, /t/) while tests involving rhyme involve the ability to differentiate between the onset and the rime components of the word ("cat" -> /c/, /at/). Thus, rhyming and segmentation abilities should exert different influences over a child's acquisition of literacy skills. This possibility is considered below.

2.3.2. Phonological awareness and literacy development: the chicken or the egg?

It is generally accepted that phonological awareness and reading ability emerge approximately contemporaneously and that the two measures are correlated at each stage of an individual's development (Bryant & Goswami, 1987; Morais *et al*, 1987). A debate is raging, however, over the causal direction (if, in fact, a causal relationship exists) between these two constructs. Proponents of this discussion take two standpoints, suggesting that: (1) phonological awareness is a pre-cursor to reading in an alphabetic orthography, in that until a child has acquired at least a rudimentary degree of phonological awareness reading is not possible (Bishop & Adams, 1990; Goswami & Bryant, 1990; Gough, Juel & Griffith, 1992); and (2) phonological awareness is a benefit of alphabetic reading, such that reading development facilitates the child's awareness of the individual phonemes in words (Lundberg *et al*, 1988; Bertelson, de Gelder, Tfouni &

Morais, 1989). Others have reconciled these alternatives by suggesting that as a child learns to read it becomes increasingly aware of phonemes, and is able to utilise its expanding repertoire of phonological processing skills to facilitate reading development; therefore, reading ability and phonological awareness may be considered to develop in a "mutually supporting relationship" (Perfetti *et al*, 1987; Stuart & Coltheart, 1988).

Studies aimed at delineating this relationship usually take one of four forms: a) the longitudinal monitoring of phonological awareness in children as they learn to read; b) the assessment of phonological awareness in individuals with no knowledge of an alphabetic orthography, such as illiterate adults or individuals literate in purely logographic scripts; c) studies involving training in aspects of phonological awareness while the effect of this training on subsequent reading ability is monitored; and d) investigations comparing the phonological skills of subjects at different points along the reading ability continuum - i.e. dyslexic and normal readers. This latter relationship between phonological skills and reading ability in developmentally dyslexic children is considered in depth in **Chapter 3** by way of introduction to the cross-sectional studies to be reported in the present thesis. The following sections of this review will only focus on the other three types of investigation; these are considered in turn.

2.3.2. (a) A longitudinal perspective

One of the first longitudinal studies, involving the repeated testing of children on measures of phonological awareness, prior to and during the early stages of formal reading instruction, was carried out by Lundberg *et al* (1980). This study involved the administration of nine measures of various aspects of phonological ability (including tests of segmentation and blending at the syllabic and phonemic levels, tests of phoneme identification, phoneme reversal and rhyme production) and a test of reading ability, to initially pre-literate kindergarten children. Follow-up testing occurred after one year and again six months later. Analysis of these data revealed significant correlations between early phonological awareness and later reading achievement, with the measures involving phonemic analysis more strongly predicting reading ability than those involving analysis at the syllabic level. Specifically, accuracy on the task requiring phoneme reversal (and to a lesser degree rhyme production) proved to be the most accurate predictor of later reading success. No other measure of phonological awareness made a unique contribution to the prediction of later reading success.

Bryant and Bradley (1983, 1985) took this argument a stage further. They reported that not only is kindergarten sound categorisation ability predictive of later reading ability, but that phonological awareness in the pre-literate child actually exerts a causal influence over the child's eventual success in reading. It should be noted, however, that in this particular study phonological awareness only accounted for approximately 10% of the variance in later reading skill; while the influence of early phonological awareness is significant, therefore, it is by no means the only causal factor in a child's reading development.

That phonological awareness has a direct bearing on later reading ability is also reported by Mann (1984; Mann & Liberman, 1984). She reported significant correlations between measures of phonological awareness (syllable segmentation and phoneme reversal) obtained in kindergarten and reading ability one year later; no such relationship emerged between syllable reversal and reading ability. These results are again consistent with the suggestion that measures of phonological awareness exert a causal influence over subsequent reading skill.

The precise nature of this effect was assessed by Bryant, Bradley, MacLean & Crossland (1989) who undertook to investigate the influence of nursery rhyme familiarity in the 3 year old child on reading development over the ensuing three years. In support of previous reports (Lundberg *et al*, 1980; Mann, 1984; Mann & Liberman, 1984) these researchers observed that different aspects of phonological awareness (knowledge of nursery rhymes, rhyme detection and phoneme oddity) correlated differentially with later reading ability. Furthermore, these measures of phonological awareness were interrelated, such that the pre-literate child's knowledge of nursery rhymes enhanced its awareness of the constituent sounds of speech (via rhyme detection and phoneme detection) which in turn influenced subsequent reading development. Thus, the process is considered to reflect a continuous development of phonological ability which ultimately manifests itself in the child's reading ability. Further support for this suggestion derives from reports that whereas a "primitive" measure of phoneme synthesis (sound blending) predicts later reading, a more "sophisticated" measure (phoneme deletion) is both influenced by, and itself influences, reading ability in a reciprocal relationship (Perfetti *et al*, 1987). Unfortunately, however, the subjects in this study were first grade pupils with extant reading skills at the first time of testing, so it is not possible to infer from these results the prospective influence of phonological abilities in pre-literates.

This latter point highlights a common flaw of longitudinal investigations (including the ones described above) with regard to the developing relationship between phonological awareness in the pre-school child and later reading ability. The failure to take account of any reading skills of children at the first time of testing precludes the subsequent exploration of the reciprocity of the relationship between phonological awareness and reading in the earliest stages of literacy development (Wagner & Torgesen, 1987). In view of the fact that nursery education in Britain and America generally involves an introduction to the rudimentary skills necessary for reading acquisition (Adams, 1990), the finding that phonological awareness in the pre-school child predicts reading ability in the same child in grade 1 may reveal nothing more than that early reading ability predicts later reading ability (Wimmer, Landerl, Linortner & Hummer, 1991). Support for this argument is provided by Wagner & Torgesen's (1987) re-analysis of Lundberg *et al*'s (1980) data. The substantial partial correlations reported by Lundberg *et al* between the phonological awareness scores of kindergarten children and their later literacy scores mostly dropped to zero when kindergarten reading ability was controlled for.

One investigation which took account of initial reading ability was conducted by Wimmer *at al* (1991). They tested children initially in their first month at school, prior to the commencement of formal literacy training; objective tests of letter knowledge and word reading confirmed that few of the children could read. Scores on a vowel substitution task (a measure of phonological awareness) at the first stage of the study differentiated between the readers and non-readers such that the readers showed ability on this task whereas the non-readers found it extremely difficult. After just 5 months of reading instruction, however, a near-perfect performance on the task was produced by most of the children, suggesting that even a minimal amount of alphabetic reading instruction may have a dramatic effect on the emergence of elementary phonological awareness. In addition to this relationship between reading skill and phonological ability, the authors report a predictive relationship in the opposite direction, from phonological awareness prior to the commencement of reading instruction to reading ability at the end of grade 1 (with IQ and initial differences in reading ability and letter knowledge controlled for). Closer inspection of the results, however, shows that whereas children with good phonological awareness at the start of the study displayed good reading skills at the end of the study, those with initially poor phonological awareness were less consistent in their acquisition of literacy skills; while a few of these children experienced some difficulty in learning to read the majority developed good reading skills. On this basis, phonological awareness should not be considered as a *necessary* precursor to reading.

In interpreting these findings Wimmer and colleagues have suggested that it is not the presence or absence of phonological awareness in the pre-literate which is important for later reading development, but rather the ease with which the phonological skills are acquired. Children who acquired these skills spontaneously, for example, prior to reading instruction, and also children who initially displayed little phonological awareness, but whose phonological skills developed rapidly, were those who showed the greatest reading development by the end of the study. Conversely, children who experienced difficulty in acquiring aspects of phonological awareness were those who displayed the greatest difficulty in the acquisition of literacy skills (Wimmer *et al*, 1991). This finding is consistent with a great body of evidence from the reading difficulties literature (reviewed in **Chapter 3**), in indicating that phonological deficiencies are frequently observed in children with impaired reading skills (Bryant & Bradley, 1985; Snowling, 1987; Goswami & Bryant, 1990).

2.3.2. (b) Alphabetic illiteracy and phonological awareness

A seminal study of phonological awareness in adult illiterates was conducted by Morais, Cary, Alegria and Bertelson (1979). Portugese adults, who had never received any formal reading instruction and little exposure to alphabetic writing, were compared on tests of phoneme and syllable manipulation with a sample of adults who had attended adult literacy classes and who had attained a minimal level of reading skill. Results showed that half of the illiterates failed on every test whereas the scores for the literate subjects ranged from 71-91% correct. Morais *et al* concluded from these results that alphabetic literacy, at whatever stage in life it is acquired, facilitates the manifestation of phonological awareness.

Other studies involving illiterate and formerly illiterate Portugese adults (Kolinsky, Cary & Morais, 1987), illiterate Brazilian adults (Bertelson *et al*, 1989), Chinese adults literate in Chinese characters but with no knowledge of alphabetic scripts (Read, Zhang, Nie & Ding, 1986) and Japanese people who have learned to read a logographic script in combination with a syllabary (Mann, 1986), support the findings of Morais *et al*. These alphabetic illiterates were again either severely impaired or completely unable to perform certain tasks which demand explicit phonological awareness. The conclusions from these studies appear to be twofold: (1) different aspects of phonological awareness emerge, independently, at different stages of development (at least in alphabetic illiterates if not in all people), and (2) it is not literacy *per se* but specifically *alphabetic* literacy which facilitates the emergence of segmentation skills.

Two criticisms have been levelled at such studies, however. The first concerns the necessary reliance on subjects' self-report concerning their educational history and alphabetic familiarity (a factor noted as problematic by Kolinsky *et al*, 1987). Bertelson *et al* (1989) report, for example, that one of their self-professed illiterates was later found to be capable of reading 90% of the words in their reading test, while Read *et al* (1986) acknowledge that one of their high phonologically-aware alphabetic illiterates was subsequently discovered to have "a little" knowledge of the alphabetic pinyin script. The exact extent of this knowledge is unknown, however, as the researchers felt unable to give an alphabetic reading test to someone who denied being able to read an alphabetic script.

A second concern with studies involving specific, atypical, groups of subjects relates to the generalisability of the results. It is possible that the findings only relate to Portugese or Brazilian illiterates or purely logographic readers, although further empirical support is provided by other studies of adult illiterates and semi-literates (Byrne & Ledez, 1983; Liberman, Rubin, Duques & Carlisle, 1985). One critical difference between these latter studies and those of Morais *et al* and Read *et al*, however, is that the Portugese adult illiterates and the Chinese and Japanese alphabetic illiterates were unable to read alphabetic writing because they had never received instruction in these skills; their lack of phonological awareness may be the result of a lack of alphabetic literacy training rather than deficient phonological abilities. The reading problems of the adult illiterates in the studies by Byrne and Ledez (1983) and by Liberman *et al* (1985), in contrast, may be the result of pre-existing deficiencies in phonological processing, of poor reading instruction or of a combination of the two. This disparity between the studies precludes the drawing of inferences concerning the direction of causality of the relationship between phonological awareness and reading ability.

2.3.2. (c) Experimental/ training studies:

If phonological awareness training has a positive effect on reading acquisition then it may be inferred that that particular aspect of phonological awareness plays a causal role in reading development. Conversely, if training in a certain reading skill enhances subsequent phonological awareness it may be argued that reading has a causal influence on the development of some aspect of phonological processing ability. By employing this approach with children at different stages of reading acquisition and at different points along the reading ability continuum it may be possible to gain a better understanding of the relationship between the development of phonological awareness and literacy.

2.3.2. (c) i) Effects of phonological awareness training on reading skill

One of the most extensive training studies to date was undertaken by Bradley and Bryant (1983). In this study groups of pre-literate children, previously identified as displaying poor phonological awareness, were trained over two years, either in rhyme and alliteration or in 'conceptual categorisation' (no phonological training). Reading measures taken at the end of the training period revealed that children who had received the phonological awareness training had progressed significantly further in reading and spelling (but not in mathematics) than those who had received no phonological training. The benefits of training in various aspects of phonological awareness have since been reported by other research groups (Lundberg, Frost & Petersen, 1988; Wagner & Rashotte, 1989; Byrne & Fielding-Barnsley, 1993)

On a more "naturalistic" level, evidence suggests that a pre-literate child's knowledge of nursery rhymes is an extremely accurate predictor of their rhyme awareness and reading ability at the age of 5 (Bryant & Bradley, 1985; MacLean, Bryant & Bradley, 1987). This effect is thought to follow two paths (Bryant, MacLean, Bradley & Crossland, 1990) the first of which is developmental. Early sensitivity to rhyme facilitates awareness of phonemes which itself enhances subsequent reading development. The second path represents the direct influence of a child's early alliterative and rhyme awareness on its later reading acquisition; this influence is thought to manifest itself through a child's reading of unfamiliar words by analogy with orthographically similar familiar words (Bradley, 1988; Goswami & Bryant, 1990). It is suggested that even incipient readers are aware of the relationship between rhyme and spelling patterns (Goswami, 1988, 1990 - see also **Section 2.2.3**), so that knowledge of phonemic similarities between words enables children to categorise written words with shared sounds. Making this awareness explicit through instruction is thought to ameliorate a young child's reading development (Bradley, 1988). The importance of early exposure to alphabetic songs and nursery rhymes to later reading ability is further emphasised by others who have suggested that this early experience provides children with a "conceptual arena within which to place letter knowledge" (Bryant & Bradley, 1987; see also Tunmer, Herriman & Nesdale, 1988; Adams, 1990) .

2.3.2. (c) ii) Effect of reading instruction on phonological awareness

While studies have demonstrated that certain aspects of phonological awareness develop prior to reading instruction, evidence that phonological awareness emerges as a benefit of reading is provided by studies investigating phonological skills in children in the early stages of reading development.

It is generally accepted that skills employed in rhyme detection and syllable manipulation tasks are present in pre-literate children as young as 2 1/2 years old (Chukovsky, 1963; Bruce, 1964), and are unrelated to reading acquisition (Morais *et al*, 1987; Goswami & Bryant, 1990). Furthermore, it is proposed that "alphabetic literacy is (almost) a sufficient indication of segmental skill... Rhyme appreciation and manipulation do not require segmental analysis" (Morais *et al*, 1987, p. 435). It is skills based on "analytic awareness", such as are required for the manipulation of sub-syllabic segments of speech, which are claimed to be absent in children prior to the commencement of reading instruction (Lundberg *et al*, 1988). Whether phonological processing skills are the product of reading acquisition, however, or whether the development of sophisticated phonological awareness skills merely reflects the growing intellectual maturity of the child, needs to be investigated in studies employing both reading-age and chronological-age matched control subjects. This issue is addressed in **Chapter 6**.

Investigations carried out by Alegria *et al* (Alegria, Pignot and Morais, 1982; Morais & Alegria, 1992) have evaluated the effects of different types of reading instruction on subsequent phonological awareness. These researchers compared the segmentation abilities of two groups of children in the early stage of being taught to read by either a phonics or a whole-word ("look-say") approach. Unsurprisingly, the phonics group demonstrated the superior phoneme segmentation ability. Unfortunately, although the only *apparent* difference between the two groups of children was the method of reading instruction given, this cannot be guaranteed as no assessment was made of the reading abilities of the two groups prior to the onset of reading instruction. It is impossible to determine, therefore, whether differences in phonological awareness are the result of the differential methods of reading instruction, of reading ability differences, or of some extraneous factor.

In spite of attempts to link phonological awareness to experience of alphabetic reading, these studies would appear to reveal nothing more than the fact that training in some aspect of phonological manipulation (i.e. during alphabetic, phonic reading instruction) enhances phonological awareness. In view of this, and of previous criticisms, it is suggested that more stringently controlled studies are required to identify the critical aspects of phonological awareness in relation to the development of reading skills.

2.3.3. Reading and phonological awareness : a summary

A certain amount of evidence suggests that considering phonological awareness as either a pre-cursor to, or a benefit of, reading is far too simplistic. Instead it may be that some degree of ability to reflect on spoken words, possibly at the level of the onset and rime, is necessary (but not necessarily *sufficient*) to gain a fundamental appreciation of the alphabetic orthography. The rudimentary ability to focus on the onset and rime within a word, and to categorise words on the basis of these components, facilitates basic word recognition and represents the first step in the foundation of a sight vocabulary. As this sight vocabulary - and the child's word recognition ability - expands, the child is thought to focus increasingly on the sounds of words and to become gradually more aware that onsets and rimes may themselves be decomposed into smaller units (individual phonemes). The increasing complexity of a child's reflections on spoken words feeds into its reading skills which in turn engender more complex forms of phonological awareness (see Barron, 1991; Ehri, 1992; Stahl & Murray, 1994). It is suggested, therefore, that "this series of insights looks like a continuously developing ability" (Stahl & Murray, 1994, p. 232), a view also taken by Goswami and Bryant's (1990) 'Theory about Causes', described in **Section 2.2.3**.

The present review suggests that the term 'phonological awareness' does not relate to a single entity but to a developmentally heterogeneous construct which encompasses numerous aspects of linguistic processing, such as phoneme blending, segmentation, alliterative awareness and rhyme production. The relationship between a pre-literate's phonological awareness and its ultimate reading ability appears to be rather more complex than previously appreciated. Extensive research into the exact nature of phonological awareness, its development and its relationship with a child's reading development has produced two important revelations.

The first of these is that the different skills which constitute phonological awareness follow their own time course, so that overall there appears to be a gradual development in phonological processing ability (Lomax & McGee, 1987; Bryant *et al*, 1990). A great deal of evidence indicates the presence of rudimentary aspects of phonological awareness in the pre-literate child (Juel, Griffith & Gough, 1986; Ball & Blachman, 1988; Bryant *et al*, 1990). These aspects include the ability to isolate and manipulate sounds at the level of the syllable (Rosner & Simon, 1971), and the perception of rhyme (Lenel & Cantor, 1981; MacLean *et al*, 1987). More sophisticated aspects of phonological awareness, involving, for example, the perception and manipulation of phonemes, only appear to emerge following the onset of formal reading instruction (Perfetti, Beck & Hughes, 1981; Treiman & Baron, 1983; Adams, 1990).

The second discovery is that young children who demonstrate superior performance on tasks requiring the detection of syllables (Mann & Liberman, 1984), rhymes (Bradley, 1988; Ellis & Large, 1987) or phonemes (Stanovich *et al*, 1984; Tunmer & Nesdale, 1985) are those who demonstrate the greatest ease in the acquisition of reading skills. In fact, it is argued that even when IQ, socio-economic status and verbal memory are controlled for (Bradley & Bryant, 1985; MacLean *et al*, 1987), phonemic awareness in the pre-school child is the most accurate predictor of later reading ability currently available (Tunmer & Nesdale, 1985; Ellis & Large, 1987; Adams, 1990).

In addition to the direct relationship which exists between phonological awareness and reading development, phonological ability is also thought to exert an indirect influence over an individual's literacy skills via its involvement in the storage of information in verbal memory. This relationship is discussed below.

2.4. Cognitive correlates of reading II: phonological memory

Gathercole, Willis and Baddeley (1991) have argued that "Children with good temporary phonological memory skills should more readily learn the sounds of new words than children of less adequate skills" (p. 403). In view of the importance of the relationship between phonological processing skills and reading ability, as discussed above, the implications of Gathercole *et al*'s pronouncement for reading development are clear. Individual differences in reading ability may reflect concurrent differences in the capacity and processing efficiency of short-term phonological memory (Bryant & Bradley, 1985; Johnston, Rugg & Scott, 1987; Thomson, 1988). The precise role played by phonological memory in the impaired reading of dyslexics is discussed in **Section 3.3**; the current review will focus specifically on the relationship between short-term memory and reading development in the normal reader.

2.4.1 Phonological memory: a definition

It may be politic from the start to clarify the terminology employed in memory research. Researchers interested in the relationship between reading ability and the capacity to remember information over the short-term have variously referred to this latter concept as "short-term memory" and as "working memory". The terms have, on occasion, been used synonymously in the literature (see, for example, Siegel & Linder, 1984), although it is argued that the two cannot be equated (Brainerd & Kingma, 1985; Shankweiler & Crain, 1986). Both systems are conceptualised as being responsible for the temporary storage of information, generally in the form of phonological codes (see **Section 2.4.2**), and both are prone to decay in the absence of active rehearsal (Schweickert & Boruff, 1986; Daneman & Tardif, 1987). The subtle difference between the two lies in the functional significance of the storage. The label 'short-term memory' refers to a static, limited capacity system in which information is stored ready for subsequent recall (Daneman & Tardif, 1987; Penney, 1989; McDougall & Hulme, 1994), the term 'working memory', it is argued, relates to a dynamic, tripartite system which stores information temporarily while some cognitive operation is performed on it (Baddeley, 1990; Siegel, 1994; Hulme & Roodenrys, 1995). While this distinction may appear somewhat pedantic it does represent a fundamental difference in the conceptual nature of the two memory systems. To avoid the definitional problems inherent in the adoption of one term in preference to the other the current review will employ the rather more neutral term, phonological memory, in reference to the temporary storage of linguistically coded information (see also Gathercole *et al*, 1991; Michas & Henry, 1994).

2.4.2 Representation of information in phonological memory

Although the precise details of representations in phonological memory are unclear they are generally regarded as being "phonemic" in that verbal information is recoded and stored in the form of its phonological features (Baddeley & Hitch, 1974); as such these representations may be equated with "inner speech". This latter suggestion has been criticised, however, as the concomitant implication, that the representations might include morphological and syntactic information, is inconsistent with the notion that the role of phonological memory is merely to *support* high level language comprehension (Baddeley, 1986; Mattingly, 1991).

Whatever the precise nature of the representations, as mentioned previously, they are subject to rapid decay although the traces may be refreshed by a process of sub-vocal rehearsal (Baddeley, 1986; Schweickert & Boruff, 1986). It is this sub-vocal rehearsal which is arguably responsible for constraining the amount of information which may be stored. The capacity of phonological memory is estimated at between 1.5 and 2 seconds (Hulme, Thomson, Muir & Lawrence, 1984; Hitch, Halliday & Littler, 1989). The number of items that can be maintained in memory is thought to reflect the number that can be subvocally rehearsed within this time; i.e. only items which are refreshed (sub-vocalised) before their traces decay to a level beyond which they can no longer be recognised at retrieval, will be remembered. The implications of this relationship between rate of vocalisation and developmental increases in memory span are discussed in **Section 2.4.3**.

Psychophysiological support for the involvement of some form of sub-vocal rehearsal in phonological memory is offered by Paulesu, Frith and Frackowiak (1993). These researchers took measures of regional cerebral blood flow with concomitant positron emission tomography while subjects performed phonological memory and rhyme detection tasks. Results revealed increased activation localised to the supramarginal gyrus of the left hemisphere and to the region surrounding Broca's area, consistent with the elicitation of sub-vocal rehearsal (see **Section 4.1** for a discussion of the involvement of these cortical regions in linguistic processing).

2.4.3 Developmental changes in phonological memory capacity and processing efficiency

In view of this intimate relationship between phonological memory skills and speech mechanisms it is hardly surprising that changes in linguistic ability are implicated in developmental increases in memory span (see Hulme & Roodenrys, 1995).

By approximately 4 years of age children are reported to be as vulnerable to the word length effect (the shorter the words to be remembered the greater the number that can be rehearsed and subsequently recalled (Baddeley, Thomson & Buchanan, 1975)) and to the phonological similarity effect (reflected in the poorer recall of phonologically similar than dissimilar items (Henry, 1991)) as are older children and adults (Hulme *et al*, 1984; Ford & Silber, 1994). This would suggest that the operational characteristics of phonological memory are fully developed by the age of 4, yet a child's memory capacity is found to increase dramatically from this young age until adolescence (Hulme & Mackenzie, 1992; Roodenrys, Hulme & Brown, 1993). Thus, proposed explanations for this increase in capacity have focused on more subtle developmental changes within phonological memory, changes including increases in articulation rate and in processing efficiency.

Undoubtedly this developmental increase in memory capacity occurs contemporaneously with an increase in the rate of a child's articulatory capabilities (Henry & Millar, 1991; Roodenrys *et al*, 1993; see also Hulme & Roodenrys, 1995); furthermore, rate of articulation is reportedly able to account for individual differences in memory span, not only across different ages but also across different types of stimuli (Standing, Bond, Smith & Isely, 1980; Schweickert & Boruff, 1986) and different languages (Ellis & Hennelly, 1980; Naveh-Benjamin & Ayres, 1986). Such evidence has been interpreted as indicating that developmental increases in memory capacity reflect the increasing efficiency of underlying phonological processes (Hulme & Tordoff, 1989; Kail, 1992).

However convincing the argument relating memory span and articulation rate, developmental increases in speech rate may not be the sole reason for age-related changes in phonological memory capacity. Even when words are equated for the speed with which children of different ages can articulate them, for example, differences in memory span are still evident (Henry & Millar, 1991), while observed correlations between increasing memory capacity and decreasing response rates have proved non-significant with the effect of age partialled out (Stanovich, Nathan & Zolman, 1988; Rapala & Brady, 1990). It is suggested, therefore, that future studies look beyond the developmental effects of speed of phonological processing in the investigation of changes in memory capacity (Campbell & Wright, 1990; Henry, 1991; Cowan, Day, Saults, Keller, Johnson & Flores, 1992).

Having dismissed speed of articulation as the sole protagonist in the developmental increase of memory span, evidence is accumulating for the involvement of other factors, including output rate and the involvement of long-term memory representations. The word length effect, for example, is explained as arising partly from the decay of phonological representations while the subject is articulating its response (Henry, 1991; Cowan *et al*, 1992; Cowan, 1992). Alternatively, it is possible that rate of articulation may interact with output rate so that memory span benefits from rapid reactivation of the decaying memory traces during pauses in response (Cowan, 1992). The influence of long-term memory on phonological memory capacity is thought to be via the reconstruction of decaying memory traces, such that those which have decayed beyond the point at which are they are recognisable may be reconstructed through recourse to their long-term representations (Hulme, Maughan & Brown, 1991; Schweickert, 1993). The involvement of long-term memory mechanisms has been invoked to explain developmental increases in memory span independent of speech rate (Swanson, Cochran & Ewers, 1990; Roodenrys *et al*, 1993).

2.4.4. Phonological memory span, linguistic processing and literacy

It is hardly surprising that phonological memory skills have been implicated in various linguistic abilities including vocabulary acquisition (Gathercole, Willis, Emslie & Baddeley, 1992; Michas & Henry, 1994) and language comprehension (Mann, Shankweiler & Smith, 1984; Smith, Mann & Shankweiler, 1986), in both children and adults. In addition to its obvious role in the processing of spoken language, a burgeoning accumulation of evidence has indicated that the ability to retain information in phonological memory is a key factor in the acquisition of literacy skills (Wagner & Torgesen, 1987; Crain, Shankweiler, Macaruso & Bar-Shalom, 1990). It is this latter relationship which is of particular interest to the current thesis.

Phonological memory is thought to play two important roles in the reading process. One of these is in the identification of individual words, such that phonological memory acts as a temporary storage system during the grapheme-phoneme translation of unfamiliar words; the resultant sounds may be stored, in sequence, during this process prior to being blended into a single word (Baddeley, 1986). A second role of memory is in text comprehension. The meaning of sentences transcends the meaning of the individual words of which they are formed, so that to understand a written sentence a reader must be able to retain information about words read early on and to relate these to later words (Daneman & Carpenter, 1980; Daneman, 1988). In the absence of this temporary storage a reader would be continually re-reading phrases and sentences to make sense of recently processed text. Fluent reading is thought to involve a complex interaction of processing and temporary storage requirements (Daneman & Tardif, 1987).

If efficiency of phonological retention is related to success in the acquisition of literacy skills then measures of phonological memory span in the pre-literate child should correlate with reading ability at some later stage of development. Such a finding has been reported for memory span for phonologically non-confusable word strings (Mann, 1984; Mann & Liberman, 1984) and also for sentence memory span (Jorm *et al*, 1986).

Unfortunately, however, as with many such studies, these investigations are flawed by having taken no objective measure of reading ability at the first time of testing (see **Section 6.1.5** for a critique of longitudinal studies). Although it would appear that efficiency of phonological coding in memory exerts an influence over later reading development, these studies permit no investigation of the possible reciprocal influence of reading ability on phonological memory span. While evidence linking phonological memory span with subsequent reading skill is limited, strong correlations are reported between the two measures taken contemporaneously in primary school children (Hulme, 1988) and in adults (Masson & Miller, 1983).

2.4.5. Phonological memory capacity, phonological processing and literacy

In view of the evidence that memory and reading ability are related via phonology, relatively little research has been undertaken to investigate the relationship between explicit phonological awareness, phonological memory and literacy. One study which has broached this relationship is that of Alegria *et al* (1982). As reported in **Section 2.3.2 (c) ii**, these researchers investigated the influence of phonics versus whole word literacy training on memory span over 4 months of reading instruction. Although the two groups of children differed in their phonemic segmentation abilities at the end of the 4 month period, no differences were found in memory span. This would appear to argue against the possibility that reading instruction in which the phonological features of words are explicitly taught increases the efficiency of phonological encoding in memory. Unfortunately, however, this study was prone to methodological flaws, such that no measures of memory span or reading ability were taken prior to the onset of reading instruction and the two samples were limited in size (32 children in each). The findings of this study have been regarded with some scepticism (Wagner & Torgesen, 1987).

The question of whether phonological awareness (as assessed using a rhyme oddity task) and phonological memory (non-word repetition and digit span) are merely two aspects of a common phonological processing ability, or whether they reflect differentiable abilities has been addressed by Gathercole *et al* (1991). They report that whereas both phonological memory measures correlated with vocabulary knowledge at ages 4 and 5, they were related to reading ability only in the 5 year old children. Conversely, performance on the rhyme oddity task did not correlate significantly with vocabulary knowledge at either age although it was related to ability on a primary reading measure at both ages. The implication of these results is that although phonological memory and phonological awareness appear to share a common component, they also make their own differential contributions to vocabulary knowledge and to reading development. The finding that rhyme awareness relates to reading ability from the early stages of a child's academic life supports the proposal of Goswami and Bryant (1990) that rhyme awareness emerges early in a child's cognitive development and is causally related to later achievements in the acquisition of literacy skills. That phonological memory only emerged as important to reading after a year of instruction (Gathercole *et al,* 1991) was explained by recourse to stage models of reading development which outline the nature of the reading skills used by children at different stages of literacy acquisition. After approximately a year of reading instruction the process of reading is thought to undertake a shift away from the use of primarily logographic strategies towards the employment of alphabetic decoding strategies (Frith, 1985). Thus, in the early, logographic, stages visual processing skills are of paramount importance to successful reading (Ellis & Large, 1988). By the time the child enters the alphabetic stage and starts to employ grapheme-phoneme translation the emphasis has shifted to highlight the pre-eminence of phonological memory skills, both for the learning of the basic rules of grapheme-phoneme translation (Byrne & Fielding-Barnsley, 1989), and also for the temporary storage of individual sound segments which result from alphabetic decoding (Baddeley, 1979 - see **Section 2.4.4**). See **Section 2.2** for a detailed outline of models of reading development.

Although Gathercole *et al*'s findings accord with existing models of reading development, a major criticism of this investigation must be mentioned. This concerns the reading ability - or lack of it - of the children at each stage of the study. The majority of the children at the age of 4 were unable to read; even one-third of the 5 year old children showed no reading ability on a single word reading test. This calls into question the validity of the conclusions drawn from this study.

A more recent attempt to investigate the relationship between phonological awareness, phonological memory and reading ability has been undertaken by McDougall, Hulme, Ellis and Monk (1994). This study involved presenting a sample of 7 to 9 year old children with a battery of tests including measures of rhyme oddity and phoneme deletion (phonological awareness), memory span for one, two and three syllable words and for abstract forms, speech rate and single word reading ability. The children were subsequently divided on the basis of this latter score into three reading ability groups. While no between-group differences were observed for memory of abstract shapes, memory span for words significantly differentiated between the reading ability groups (in the expected direction); these differences were eliminated when speech rate was controlled for. Phoneme deletion ability and rhyme awareness independently predicted reading ability, supporting suggestions that different phonological awareness tasks map different aspects of phonological awareness (see Yopp, 1988; Goswami & Bryant, 1990). Articulation rate also predicted reading (with phonological memory and phonological awareness controlled for), but memory span was unable to independently predict reading ability after the effects of speech rate had been removed. These findings were interpreted as indicating that speed of articulation indexes the speed and efficiency of the activation of phonological representations in memory.

2.4.6. Phonological memory and literacy: a summary:

Learning to read is a tremendous feat of memory. Therefore, evidence indicating the importance of phonological memory capacity and processing efficiency to the acquisition of competent reading skills is unsurprising (Bryant & Bradley, 1985; Johnston *et al*, 1987; Thomson, 1988). Phonological memory skills are also implicated in competent reading, via the storage of individual words within sentences, to facilitate the comprehension of text (Daneman & Tardif, 1987; Daneman, 1988).

While the precise relationship between phonological memory span and reading development remains to be delineated, what is apparent on the basis of the preceding review is that the two are intricately related across the developmental spectrum. The mechanisms which may underlie this relationship have been discussed in terms of the speed and accuracy of linguistic, i.e. phonological, processing (see Hulme & Roodenrys, 1995). Thus, the importance of including measures of both phonological processing ability and phonological memory skills in any study of the cognitive processes involved in reading, cannot be over-emphasised.

In view of the fact that the reading process depends on the integration of both linguistic *and* visual information (Cornelissen, Bradley, Fowler & Stein, 1992), investigations of the cognitive correlates of reading which have focused solely on the former to the exclusion of the latter would appear to be rather misguided. Recent investigations of the importance of visual processing skills to competent reading have been relatively few, however; these are discussed below.

2.5. Cognitive correlates of reading III: visual perception

Some researchers argue that early reading is predominantly visual, such that in the early stages of reading development children identify words on the basis of their orthography rather than by decoding them via grapheme-phoneme translation (Frith, 1985; Ellis & Large, 1988; Gathercole *et al*, 1991; see **Section 2.2**). On this premise children with poor visual skills would be expected, intuitively, to experience greater difficulty with learning to read than children with competent visual perception. A growing body of evidence from investigations of children with reading impairments has indicated that this may be the case (Livingstone, Rosen, Dislane, & Galaburda, 1991; Stein, 1991; Cornelissen, Bradley, Fowler & Stein, 1994); the implications of infantile visual disturbances for developmental dyslexia are discussed in **Section 3.4**.

Visual perceptual skills are also implicated, to some extent, in fluent reading; visual information about individual letters and word forms is the first source of information in word recognition (Massaro & Sanocki, 1993). Predictive and correlational investigations of competent readers have shown that reading ability may be predicted by visual perceptual skills, as indexed by measures of visual sequencing (Sterrett, Martin & Rudnick, 1971; Goldberg & Guthrie, 1972), visible persistence of images (Lovegrove & Brown, 1978) and speed of processing of visual information (Lovegrove & Brown, 1978; Mazer, McIntyre, Murray, Till & Blackwell, 1983). Electrophysiological activation (visual-evoked potentials) in the parietal region of the left hemisphere has also distinguished between readers of varying abilities (Conners, 1971).

2.5.1. The development of visual perceptual skills:

One paradigm which has been employed to examine the development of visual perception in children is visual crowding. This task involves the presentation of target stimuli, including letters (Atkinson, Anker, Evans, Hall & Pimm-Smith, 1988; Geiger & Lettvin, 1986), letter-like forms (Loomis, 1990) and abstract shapes (Banks & White, 1984), surrounded by similar, distractor, forms; the subject's task is to identify the target form. Visual discrimination ability is expressed in terms of a "crowding ratio" - the size of the smallest target identified when surrounded by distractor forms, compared with the smallest target identified in isolation. Crowding effects (i.e. large crowding ratios) have variously been attributed to the influence of sensory impairments (Banks, Bachrach & Larson, 1977) and to a lesser ability to divide attention between stimuli (Ruddock, 1991). It is possible that a minority of children, with such subtle impairments in their visual perceptual abilities, will experience delays in their acquisition of literacy skills on entering formal education (Atkinson, 1991). Whether these impairments are the result of delay or dysfunction, however, remains to be determined (see **Section 3.4**).

Using this paradigm Atkinson *et al* (1988) report that the visual discrimination abilities of 5 to 7 year old children are generally comparable to those of adults, both of which are greater than in 3 to 5 year olds. Thus, it would appear that the development of normal visual perceptual abilities is largely a maturational effect which is complete by the time a child starts school. Unfortunately this maturational increase in visual perceptual acuity appears not to be the norm for all children. Within the sample of older children, for example, a certain degree of difficulty was encountered on this task, causing some to be labelled as "visually delayed"; these children had suffered from minor impairments in visual performance, including abnormal visual alignments, in infancy. No measure of reading ability was taken in this particular study, however, thus precluding the drawing of inferences regarding the particular effects of these delays on reading development (Atkinson *et al*, 1988).

In young children visual forms are recognised relatively independent of orientation (Richardson, 1984). This would offer support to suggestions that delays in the emergence of visual perceptual abilities may be involved in the visual errors (i.e. letter reversals) made by some children during reading (this issue is addressed further in **Chapter 3**). Further support derives from the findings of Stein and colleagues (Stein, 1991; Cornelissen *et al*, 1992) through their investigations of the emergence of binocular (vergence) stability in children. This refers to the ability of the individual to direct the convergence of the two eyes to a particular point. It is reported that at 5 years of age 50% of children present evidence of unstable vergence, with this figure decreasing by 8% per year thereafter (Stein, Riddell & Fowler, 1986). The attainment of stable vergence would have obvious implications for a child's reading development.

2.5.2. Visual perceptual skills and reading: a summary:

It would appear that visual perceptual skills early on in a child's life may have implications for reading development although, as mentioned above, there is a relative paucity of studies comparing the visual perceptual skills of competent readers at different ages. To the author's knowledge, no longitudinal study has monitored the changing role of visual processing skills in normal reading development. Such evidence as there is derives largely from studies of children with reading impairments. The precise relationship between visual skills and reading ability in normal children is far from clear. Of course, this is likely to be due to difficulties in defining exactly what constitutes visual processing, and in identifying tasks which specifically tap this construct (Stein, 1991). This issue is addressed in **Chapter 6**.

2.6. Conclusion:

The above evidence highlights the importance of specific cognitive skills (phonological awareness, memory capacity and visual perceptual abilities) in the successful acquisition of reading skills. It is not *sufficient* to focus exclusively on the child in whom these skills are acquired successfully, however. As William James (1890) observed, "To study the abnormal is the best way of understanding the normal". An investigation of the cognitive profiles of children who *fail to develop* age-appropriate reading skills might further elucidate the specific factors necessary for successful reading. This is considered in the next chapter.

~ CHAPTER 3 ~

The psychology of developmental dyslexia

> *"We don't say babies are dyslexic although we may say some actresses are. We don't say people who have never been to school and have never learned to read are dyslexic, we say they are illiterate or semiliterate... Use determines meaning and usage has already determined that 'dyslexia' and 'dyslexic' have entered the language as useful terms of no greater specificity or medical pretension than 'dyspepsia' or 'dyspeptic'."*
>
> Young & Tyre, 1983, p. 20

3.1. Developmental dyslexia: Defining the indefinable?

As noted by Young and Tyre (1983), the diagnosis of dyslexia and the application of the label 'dyslexic' to children who unexpectedly fail to acquire a conventionally acceptable level of literacy are controversial despite a century of research into the study of reading impairment (Farnham-Diggory, 1985; McManus, 1991). Opposition to the concept of dyslexia has been so vehement in some quarters that acceptance of it as an entity has been likened to an acceptance of the belief that the earth is flat (Whittaker, 1982).

3.1.1. Contemporary notions of developmental dyslexia

In spite of the controversy which surrounds its identification, as intimated above, the present thesis is concerned with developmental dyslexia in children. As noted in **Section 1.1**, the label "developmental dyslexic" is generally applied to children whose failure to acquire reading skills commensurate with their intellectual ability could not otherwise be explained in terms of adverse social or educational conditions, or by neurological damage

(Kamhi, 1992; Galaburda, 1994). This definition contrasts with that of "acquired dyslexic", the descriptive label for individuals whose previously normal reading skills are impaired by accident or disease (see Ellis, 1984; Seymour, 1987). It is the former type of dyslexia with which the present thesis is concerned.

The aforementioned application of the term "developmental dyslexic" is based on exclusionary criteria, in that it only refers to children whose reading impairments could not otherwise be explained in terms of neurological damage, sub-normal intellectual capacity, psychological factors (lack of motivation or emotional immaturity), or adverse socio-economic or educational conditions (Pavlidis, 1990). Thus, dyslexia is specifically distinguished from general retardation, i.e. the "garden variety" poor reader (Stanovich *et al*, 1986 - see **Section 3.1.2**). Defining what dyslexia is not, however, appears to be somewhat easier than identifying exactly what it is, hence the persistent inability amongst researchers to produce a universally accepted definition of the disorder (see, for example, Fletcher & Morris, 1986; Hulme, 1987; Rispens & van Yperen, 1990).

One concept on which researchers agree is that dyslexia refers to some discrepancy between an individual's *expected* and *observed* reading ability (Ellis, 1984; Frith, 1985). It is the precise measurement of this discrepancy which is the locus of dispute. Over the years different criterion to assess this discrepancy have produced varying estimates of the incidence of dyslexia (Epps, Ysseldyke & Algozzine, 1983; Lindgren, De Renzi & Richman, 1985). Estimates have varied between 1-3% (Pavlidis, 1990), 3.18% (Bullock report, 1975), 3.5-6% (Yule, Rutter, Berger & Thompson, 1974), 4-18.3% (Rispens & van Yperen, 1990), 10.9-37% (Forness, Sinclair & Guthrie, 1983) and anywhere between 5.3-69.6% (Epps *et al*, 1983) depending on the area, the country, the researcher involved, and the particular measure employed. The incidence of dyslexia appears to depend, therefore, "on where one looks, how one looks, what one is looking for, and on who is looking" (Young & Tyre, 1983). The importance of producing an operational definition of dyslexia cannot be over-emphasised.

In response to such confusion, and in an attempt to remove the ambiguity of the diagnosis, the World Federation of Neurology (1968) defined developmental dyslexia as, "a disorder manifested by difficulty in learning to read despite conventional instruction, adequate intelligence and socio-cultural opportunity. It is dependent upon fundamental cognitive disabilities which are frequently of constitutional origin". Unfortunately, in its attempts to clarify the issue this definition has also received its share of criticism and has prompted the questions: what is "conventional instruction"? What is "adequate intelligence"? What is "socio-cultural opportunity"? Which particular "cognitive disabilities" distinguish dyslexia from specific reading retardation? What is meant by "frequently of constitutional origin"? (see Rutter & Yule (1975) for a detailed criticism). Nothing is revealed about the extent of the difficulties experienced, of their possible cause or of their effects (Young & Tyre, 1983). Furthermore, this particular definition of dyslexia is circular. All it reveals is that children with reading impairments have unexplained "difficulty in learning to read".

Similar charges of speciosity have been levelled at other attempts at defining exactly what is involved in the identification of dyslexia (for reviews see Miles & Miles, 1990; Pavlidis, 1990; Beaton, 1995 - submitted for publication); the apparent futility of these definitional attempts is summed up in the following way: "Dyslexia means, quite literally, being unable to read. Children who experience difficulty learning to read are frequently called dyslexic, but their difficulty does not arise because they are dyslexic... they are dyslexic because they cannot read. To say that dyslexia is a cause of not being able to read is analogous to saying that lameness is a cause of not being able to walk" (Young & Tyre, 1983).

3.1.2. Dyslexia and IQ

A further controversy in the reading development literature is a fundamental dispute concerning the importance of IQ in the identification of dyslexia. Specifically, it is suggested that a consideration of the child's overall IQ is necessary in order to differentiate between children with "specific reading retardation" (dyslexia) and "garden variety" poor readers. The former are identified as children whose reading is below expectations on the basis of their age and IQ, the latter as children whose poor reading is in line with expectations in view of their generally low academic attainment (Pilliner & Reid, 1972; Yule & Rutter, 1985).

Although a handful of dissenting voices has suggested that IQ is either irrelevant (Siegel, 1989) or unnecessary (Merrell & Shinn, 1990; Aaron, 1991) to the classification of dyslexia, these are certainly in the minority. The consensus opinion is that IQ *is* relevant to the definition of dyslexia precisely to ensure that the differential reading skills of competent and dyslexic readers are not the result of general differences in aptitude (Snowling, 1991; Shankweiler, Crain, Katz, Fowler, Liberman, Brady, Thornton, Lundquist, Dreyer, Fletcher, Stuebing, Shaywitz & Shaywitz, 1995)

3.1.3. Subtypes of developmental dyslexia

Attempts have been made to identify subgroups within the dyslexic population. These subgroups are generally formed either on the basis of clustering of observed functional impairments (Boder, 1973; Fletcher & Satz, 1985; Bakker, 1990), or by drawing analogies between the impairments of individual developmental dyslexics and acquired dyslexics (Seymour, 1986; Castles & Coltheart, 1993). The resultant classifications have generally involved distinguishing between predominantly 'auditory/ linguistic' and 'visual' reading problems: dysphonetic and dyseidetic dyslexics (Boder, 1973; Fried, Tanguay, Boder, Doubleday & Greensite, 1981), phonological and surface/morphemic dyslexics (Temple & Marshall, 1983; Seymour & MacGregor, 1984) and P- (perceptual) type and L- (lingual) type dyslexics (Bakker, 1986, 1992). Whereas a great deal of evidence supports the classification of dyslexic children with auditory/ linguistic impairments (Bruck, 1992; Stothard & Hulme, 1995), developmental dyslexics who display purely visual impairments are rare (Felton & Wood, 1989; Stein, 1991). Of course, it is possible that this paucity of evidence of visual impairments in dyslexic children may be an artifactual result of the general difficulty in defining what constitutes visual processing, as discussed in **Section 2.5**.

The division of developmental dyslexics into subgroups has been criticised. Difficulties validating the measures employed in the definition of the groups, and the recurrent tendency to focus on what dyslexia is not rather than on what it is, have hampered classifications based on clustering of correlates and functional impairments (see Snowling, 1991). Comparisons between acquired and developmental dyslexias have also been criticised on the basis that it is not possible to equate the brain systems of adults who have lost pre-existing skills through brain damage with children who display no overt neuropsychological damage yet who experience difficulty in the normal acquisition of literacy skills (see Miles & Miles, 1990). The diagnosis of acquired dyslexia is based on the assumption of functional modularity (Bertelson & de Gelder, 1990). Modular processes that are independent, or "informationally encapsulated" (Fodor, 1983), in adults may be interactive in children, thus making 'absolute' deficits unlikely and invalidating conclusions drawn about children's abilities and deficits on the basis of these abilities in adults (Hulme & Snowling, 1991). Furthermore, there is evidence to suggest that rather than experiencing just one type of impairment a number of children with dyslexia experience both visual-perceptual and auditory-verbal deficits (see Satz, Morris & Fletcher, 1985).

It is now generally agreed, therefore, that dyslexics do not fall into homogenous subgroups, and attempts to place them into distinct groups have been largely abandoned in favour of investigations of the 'core cognitive deficits' associated with dyslexia (Wilding, 1989; Snowling, 1991; Castles & Coltheart, 1993). By comparing the cognitive profiles of competent and dyslexic readers it may be possible to gain a clearer insight into the problems experienced by dyslexics and thereby not only describe, but also explain, the cognitive deficits underlying developmental dyslexia.

Critchley (1970) suggested that "dyslexia implies vastly more than a delay in learning to read, which is but the tip of the iceberg". Over the 25 years since he made this observation researchers have made considerable advances in uncovering the 'body' of the iceberg which underlies the overt reading problems of developmental dyslexics. In view of the established importance of phonological processing, phonological memory and visual perception on normal reading development (see **Chapter 2**), it is these areas which have been investigated with regard to their bearing on the abnormal reading development of dyslexics, as discussed below.

3.2. Cognitive deficits and dyslexia I: phonological awareness

As noted in **Chapter 2**, the ability to decompose unfamiliar words, to apply grapheme-phoneme rules and then to blend the sounds into a coherent word is vital to the process of reading in the incipient reader. Of the utmost importance to the performance of this process is the appreciation that words *can* be broken down into their constituent sounds; this is one aspect of phonological awareness (Stahl & Murray, 1994; Muter, 1994). A vast amount of evidence has implicated impaired phonological processing in dyslexia. This is indexed by dyslexics' poor performance on tests of rhyme awareness (MacLean *et al*, 1987; Holligan & Johnston, 1988), rhyme production (Lundberg *et al*, 1980), phoneme segmentation (Snowling, Stackhouse & Rack, 1986; Cataldo & Ellis, 1990), alliterative awareness (Bryant *et al*, 1990), verbal repetition (Brady, Poggie & Rapala, 1989; Snowling, 1991) and verbal naming (Katz, Shankweiler & Liberman, 1981; Snowling, van Wagtendonk & Stafford, 1988). Thus, the relationship between phonological impairments and developmental dyslexia is well established (Rack, Snowling & Olson, 1992; Hulme & Snowling, 1992). Indeed, on the basis of such evidence Stanovich (1990) has proposed that dyslexia may be considered to be a manifestation of a "core phonological deficit" (see also Kamhi & Catts, 1989; Scarborough, 1990).

3.2.1. Delineating the relationship between phonological impairments and dyslexia

Explanations for the aetiology of these phonological impairments have focused primarily on notions of deficiency or delay, i.e. whether dyslexics' phonological problems are the result of fundamental *deficiencies* or of developmental *delays* (whether at the cognitive or the biological level - see **Section 4.3**). Empirical support for the former contention derives from observations that the phonological awareness of developmental dyslexics fails to show the improvements with age - or with reading skill - seen in normal readers. Dyslexics are reported to perform more poorly on tasks of phonological awareness than both normal readers of the same chronological-age and normal readers of the same reading-age (Manis, Custodio & Szeszulski, 1993; Stothard & Hulme, 1995). Furthermore, dyslexics' word recognition difficulties and phonological processing deficiencies are generally present throughout life (Read & Ruyter, 1985; Manis & Custodio, 1991; Bruck, 1992). These findings have led to suggestions that the deficient phonological awareness which initially impedes the acquisition of reading skills in dyslexics persistently impairs their reading development (Bruck, 1992). While dyslexics eventually acquire word recognition skills this may be predominantly through the use of visual strategies, with little interaction between orthographic and phonological codes. Thus, the child's phonological skills are not promoted and word recognition remains weak (Bruck, 1992; Byrne, Freebody & Gates, 1992).

The alternative hypothesis proposed to explain the relationship between impaired phonological awareness and dyslexia is couched in terms of delays in the process of normal reading development (Seymour, 1986). As detailed in **Section 2.2**, the incipient reader is generally considered to pass through a series of stages in the acquisition of fluent literacy skills. In the context of these models of reading development dyslexia has been conceptualised as occurring when a child 'fails' to make the transition from the visual (orthographic/ discrimination net guessing) stage to the phonological (alphabetic/ sequential) stage of reading (see Marsh *et al*, 1981; Seymour & MacGregor, 1984; Frith, 1985). Similarly, in the context of Goswami and Bryant's (1990) model, children who approach formal literacy instruction without phonological awareness will be severely impaired in their attempts to classify words on the basis of shared sounds, thus limiting the expansion of their sight vocabularies through the use of analogy. The implication of developmental arrest in each case is that while the child is able to recognise *familiar* words it is unable to decode *unfamiliar* words (Kitz & Tarver, 1989; Bruck, 1990, 1992). While the child may subsequently expand its lexicon via visual strategies, and even make some progress to the alphabetic phase of development with remedial instruction, this process is inefficient and fails to bring about the dramatic improvement in phonological awareness which accompanies reading development in normal readers (Bruck, 1990; Snowling & Rack, 1991; Manis *et al*, 1993). Although this explanation accounts for the observed problems of dyslexic children, the precise reason for the failure to achieve alphabetic competence remains to be determined (Frith, 1985).

It may be confidently assumed on the basis of the preceding discussion that the development of reading in a majority of dyslexics is constrained by some level of impairment in the skills which constitute phonological awareness (Stanovich, 1988; Bishop & Adams, 1990). Hulme and Snowling (1991, 1992) have suggested that the specific skills impaired in dyslexics are those involved in speech production and in grapheme-phoneme mapping. Dyslexics also experience problems when required to assimilate the orthographic and phonological representations of words, described as an "intermodal deficit" (Fletcher & Prior, 1990; Fox, 1994), and on measures of rapid speech production (Mann & Ditunno, 1990; Cornwall, 1992). It is suggested, therefore, that dyslexics may not suffer from a *global* phonological dysfunction but that their deficits are restricted to those phonological skills which are critically linked to the acquisition of literacy (Wagner & Torgesen, 1987; Holligan & Johnston, 1988; de Gelder & Vroomen, 1991 - see also **Section 2.3.**). One such skill is reflected in the child's performance on phonological memory span tasks.

3.3. Cognitive deficits and dyslexia II: phonological memory

As discussed in **Section 2.4**, the acquisition of proficient literacy skills is dependent, to a considerable extent, upon the individual child's memory capabilities. These are strongly implicated not only in the ability to link the sounds and visual forms of letters (Baddeley, 1986; Beech, 1986; Hulme, 1988), but also in the development of spoken vocabulary and general language skills (Ellis & Large, 1988; Bishop & Adams, 1990). Phonological memory has been considered as another source of impairment in developmental dyslexia (Johnston *et al*, 1987; Snowling & Hulme, 1989; Hulme & Snowling, 1992).

Dyslexics are found to demonstrate reduced memory span, relative to good readers, for various types of linguistic information, including letter strings (Siegel & Linder, 1984; Holligan & Johnston, 1988), unrelated word strings (Rack, 1985; Beech & Awaida, 1992), words in a sentence (Wiig & Semel, 1976; Mann, Liberman & Shankweiler, 1980) and strings of digits (Spring, 1976). Dyslexics' memory deficiencies are not restricted to printed stimuli, but they *are* only found when stimuli may be represented linguistically. Material such as unfamiliar faces, abstract designs or visual patterns, for example, have failed to elicit differential memory spans in good and poor readers (Katz *et al*, 1981; Liberman, Mann, Shankweiler & Werfelman, 1982; Rapala & Brady, 1990). That dyslexic children experience memory impairments on tasks requiring the recall of linguistic stimuli, but not on tasks in which the stimuli cannot be recoded phonologically, should come as no surprise considering Rapala and Brady's (1990) caution against the conceptualisation of memory capacity as a "generic pool of resources" (p. 5).

3.3.1. Phonological capabilities and memory capacity

Given the importance of phonological coding in memory, it is highly plausible that dyslexics' memory impairments are linked to their poor proficiency in the manipulation of phonological information (Jorm, Share, MacLean & Matthews, 1984; Mann & Brady, 1988; Rapala & Brady, 1990). In fact, impaired phonological memory skills in early childhood correlate significantly with poor language development in later childhood

(Taylor, Lean & Schwartz, 1989; Gathercole & Baddeley, 1990a; Mann & Dittuno, 1990). Auditory memory span has been offered, therefore, as a reliable indicator of specific learning difficulties (Miles, 1983; Thomson, 1988), leading to suggestions that this relationship is causal. These suggestions should be considered cautiously, however, in view of the possibility that reduced phonological memory skills may actually be an *effect* of poor reading, again, via the involvement of poor phonological processing (Beech, 1988; Hulme, 1988; Pennington, Van Orden, Kirson & Haith, 1991).

It is possible, of course, that differences between good and poor readers on memory tasks reflect not the *use* of phonological coding *per se*, but rather the *accuracy* of this coding. Dyslexic children, for example, tend to show an attenuated effect of phonological confusability compared with good readers (Brady, Shankweiler & Mann, 1983; Olson, Davidson, Kliegl & Davies, 1984; Siegel & Linder, 1984). When task complexity is controlled for dyslexics are found to display phonological similarity effects equivalent to those of normal readers (Johnston *et al*, 1987; Holligan & Johnston, 1988). This would suggest that both dyslexics and normal readers employ similar speech coding and retention strategies, but that these strategies operate at a lower than expected level of efficiency in reading impaired children (Gathercole & Baddeley, 1990b; Brady, 1991). This possibility, together with alternative explanations for observed impairments in phonological memory functions, is discussed in greater detail below.

3.3.2. Memory capacity

A second explanation for memory span differences between good and poor readers concerns the number of "memory slots" available to hold items of information (Miller, 1956). Developmental increases in memory span are explained as reflecting an increase in the number of slots available with age (Pascual-Leon, 1970; Halford & Wilson, 1980). A developmental lag in this increase in dyslexics would account for the differential memory spans of good and poor readers. Unfortunately, however, the number of items to be remembered is not considered to provide a valid indication of memory capacity. As discussed in **Section 2.4.3**, greater predictive power is reported for the temporal duration of the stimulus list (Hulme, Silvester, Smith & Muir, 1986; Hulme, 1987; Ford & Silber, 1994).

3.3.3. Operational efficiency of memory processes in relation to reading ability

A third area of speculation concerning phonological memory differences of good and poor readers has focused on the operational efficiency of memory processes. According to this approach apparent developmental increases in memory capacity are not actually the result of increased capacity but rather of a decrease in the amount of operating resources required for information encoding and retrieval (Dempster, 1981). Thus memory may be viewed as a limited capacity system in which greater processing efficiency is achieved with experience (Case, Kurland & Goldberg, 1982).

Two main bodies of evidence offer support to this suggestion: (1) short-term recall in normal adults suffers as the perceptual demands of a memory task (and hence the difficulty of encoding) increase (Luce, Feustel & Pisoni, 1983; Mattingly, Studdert-Kennedy & Megan, 1983). Increasing task complexity has also been demonstrated to have a significantly more detrimental effect on children with poor reading ability than on good readers (Rapala & Brady, 1990); (2) evidence from children and adults suggests a link between efficiency of phonological processing (as reflected in rate of articulation, for example) and memory span (Spring & Perry, 1983; Hulme *et al*, 1984). Furthermore, reduced phonological memory capacity is common in children with articulatory disturbances which would hinder both the input and the output stages of memory processing (Locke & Scott, 1979; Brady *et al*, 1983, 1989). Reduced efficiency of phonological processing may impair a child's ability to recognise unknown printed words, in that an increase in the level of resources required for decoding leads to a decrease in the resources available for maintaining the constituent sounds in memory in preparation for blending the isolated phonological representations into meaningful words (Wagner & Torgesen, 1987).

In fact, it has been demonstrated that even within a sample of dyslexic children, those with poor memory spans for digits perform worse on a sound blending task than those with normal digit spans; these latter children perform at an equivalent level to control children with age-appropriate reading skills (Torgesen, Rashotte, Greenstein, Houck & Portes, 1987). While these researchers make no sweeping claims about the direction of causality in this relationship, they do suggest that, for at least some dyslexic children phonological memory problems may contribute to difficulties in the application of phonological recoding strategies during reading. Support for this suggestion is offered by studies with normal incipient readers in whom blending ability is reported to increase with the rate of presentation of individual sound segments, thereby reducing memory load (Torgesen, Wagner, Balthazar, Davis, Morgan, Simmons, Stage & Zirps, 1989).

Another aspect of operational efficiency which appears to be impaired in dyslexic children is reflected in their poor performance on tasks requiring rapid verbal repetition; i.e. dyslexics are significantly slower and less accurate than good readers at enunciating multisyllabic words (Snowling, 1981) and phonologically complex non-words and phrases (Brady *et al*, 1989; deGelder & Vroomen, 1991). The speed at which a child is able to subvocally rehearse words in phonological memory may influence memory span. The faster the articulation the longer an item remains in memory (Baddeley *et al*, 1975; Hulme *et al*, 1984; but see also **Section 2.4.3**). Thus, dyslexics' impaired phonological memory for verbal material may be explained in terms of a rehearsal deficit for phonological information (Hulme, 1987). In view of the reported relationships between reading ability, phonological processing skills and rate of articulation, it may be that the acquisition of reading skills serves to improve articulation which in turn increases phonological memory span (Johnston *et al*, 1987; Ellis, 1990; Ellis & Large, 1988). Support for this hypothesis is provided by studies reporting no differences in memory span between dyslexics and reading-age matched control children (Hulme, 1981; Johnston, 1982).

3.3.4. The aetiology of phonological memory deficits in dyslexics

Whatever the precise nature of the mechanisms underlying the phonological memory differences of good and poor readers, investigations of the aetiology of these differences have generally indicated that they may represent some form of *delay* in the development of dyslexic children rather than a fundamental *deficiency.* Olson *et al* (1984), for example, observed that whereas memory span increases in a linear trend for both good and poor readers, at any point in time the memory skills of poor readers are inferior to those of chronological-age matched good readers. Evidence is also reported for a delay in the emergence of the phonological similarity effect in poor readers. The recall accuracy of normal readers tends to be detrimentally affected by phonological similarity by the age of 8 years (Conrad, 1971; Holligan & Johnston, 1988). This effect does not normally emerge in dyslexics until a much later stage of development. Rack (1985), for example, failed to elicit a phonological similarity effect in 13 year old dyslexics; others have failed to observe the effect in 9-10 year old dyslexics, and even then accuracy of recall is generally lower than that of good readers (Siegel & Linder, 1984; Bisanz, Das & Mancini, 1984).

It might be the case, of course, that phonological memory capacity and reading ability in dyslexics are both influenced by a maturational lag (Satz, Taylor, Friel & Fletcher, 1978; Siegel & Linder, 1984). Consonant with this notion is Bryant & Impey's (1986) argument that all of the problems encountered by children with specific learning difficulties should be thought of as delays in reading development, rather than as irreversible 'defects'. By describing dyslexics' problems as delays it is implied that the cognitive skills of these children will eventually 'catch up' with those of normal readers, with a concomitant improvement in their literacy skills. In fact evidence indicates that the language processing problems identified in dyslexic children are still present through adolescence (McKeever & van Deventer, 1975) and into adulthood (Scarborough, 1984; Read & Ruyter, 1985). This observation serves to highlight the need for studies to chart the emergence of cognitive skills in children at different levels of literary competence.

Evidence has indicated the possibility that reduced memory span may be a pre-cursor to dyslexia (Bryant & Bradley, 1985; Mann & Ditunno, 1990). Care must be taken, however, not to interpret such findings in terms of a causal relationship between impaired phonological memory functioning and the reading ability of dyslexic children. This may be too simplistic, as while dyslexics are *generally* poorer on phonological memory tasks than competent readers, this is not always true. Cases have been reported of dyslexics with normal memory spans for visual and auditory material (Torgeson & Houck, 1980; Torgesen *et al*, 1987). Furthermore, rather than being causally related, phonological memory impairments and dyslexia may both be the result of a third factor, possibly even a general reduction in left cerebral hemisphere functioning (Ellis, 1984). The neuropsychology of normal and abnormal reading is discussed in detail in **Chapter 4**.

On the relationship between the phonological memory and reading problems of dyslexic children, Hulme and Roodenrys (1995) caution that although the former undoubtedly contribute to the latter, they are unable to fully explain the "severe and intransigent reading difficulties" experienced by these children. It must also be considered that phonological memory skills are only one aspect of an individual's cognitive armoury which may affect the development of their other skills, including reading ability. Investigations of the precise relationship between diverse cognitive abilities must be undertaken from a broad perspective, therefore, to look for subtle, and possibly transient, relationships between cognitive ability and reading skill at different stages of a child's development.

Another facet of a child's cognitive processing abilities which must be considered in any investigation of the mechanisms underlying reading impairments is its ability to process, and discriminate between, visually presented forms.

3.4. Cognitive deficits and dyslexia III: visual-perception

Historically dyslexia was considered to be of visual-perceptual origin (Hinshelwood, 1895; Morgan, 1896; Orton, 1928). A growing awareness over the latter part of this century of the role of phonological processing in reading, however, has generally drawn the focus of investigation away from visual and towards linguistic processing, as discussed in **Sections 3.2.** and **3.3.** While the importance of verbal processing and phonological memory skills cannot be over-emphasised with regards to their bearing on dyslexia, the last few years have witnessed a general resurgence in interest in the contribution of visual perceptual skills to reading ability in dyslexics (Livingstone *et al*, 1991; Cornelissen *et al*, 1994; Spafford & Grosser, 1993; Dautrich, 1993).

Such studies have reported, for example, deficient performance of dyslexics on tasks involving the copying of complex figures (Satz & Sparrow, 1970; Eden *et al*, 1993), visual matching (Eden *et al*, 1993; Seymour & Evans, 1994), the retention of visual images in memory (Johnson & Blalock, 1987), visual orientation (Johnson & Grant, 1989) and the processing of figure/ ground stimuli (Kavale, 1982). Recent investigations have also revealed evidence implicating deficits in more fundamental aspects of visual processing, including the functioning of the transient visual system (Lovegrove, Martin & Slaghuis, 1986; Williams & LeCluyse, 1990; Livingstone *et al*, 1991). This system, which forms part of the magnocellular pathway of the lateral geniculate nucleus, includes cells specialised for the detection of orientation, movement, direction and depth perception (Lehmkuhle, Garzia, Turner, Hash & Baro, 1993; Dautrich, 1993). Research has shown, for example, that specific difficulties such as poor visual direction sense, poor binocular vergence and poor visual fixation may lead to delays in learning to read (Stein, 1991; Willows, Kruk & Corcos, 1993; Cornelissen *et al*, 1994). In fact, children with poor visual skills at any level would be expected, intuitively, to experience greater difficulty with learning to read than children with competent visual skills. Unsurprisingly, a growing body of evidence from investigations of children with reading impairments has indicated that this may be the case (Goulandris & Snowling, 1991; Livingstone *et al*, 1991; Stein, 1991; Cornelissen *et al*, 1994).

3.4.1. Visual-perceptual impairments at different stages of reading development

As discussed in **Section 2.5**, the effects of visual-perceptual disturbances on a child's reading ability may be explained in the context of models of reading development (Marsh *et al*, 1981; Seymour & MacGregor, 1984; Frith, 1985). According to these models normally developing readers progress from an initial dependence on the visual features of words during reading to a stage wherein they learn to focus on components *within* the words and translate these into their phonological representations. A child with visual impairments is disadvantaged from the most fundamental level, from recognising the visual word form at the visual (logographic) stage and subsequently through the alphabetic and orthographic stages of reading development (Frith, 1985; Stein, Riddell & Fowler, 1987). In fact, a great deal of evidence has indicated that visual processing skills represent a significant source of variance in reading ability in addition to that provided by phonological skills (Manis, Szeszulski, Holt & Graves, 1990; Manis *et al*, 1993; Valdois, Gerard, Vanault & Dugas, 1995). The longevity of such problems in reading-impaired children is exemplified by the observation that visual-perceptual problems identified in childhood are also present in adulthood (Spreen & Haaf, 1986; Manis *et al*, 1990).

As noted in **Section 2.5.1**, young children are thought to recognise visual forms relatively independent of orientation, although awareness of the importance of perspective for identification increases over time (Richardson, 1984). It is suggested that reading-impaired children, for some reason, may fail to appreciate invariant details in the visual environment in the same way that normal readers do (Feagans & Merriwether, 1990). An impaired ability to discriminate between visual forms would explain incidences of letter confusions and reversals in dyslexic children (Gibson, 1969; Critchley, 1970). Gibson (1969) explained the implication of visual perceptual deficits by looking at their effects in the identification of letter forms. A reversal of the letter "b", for example, transforms it into a "d", while an inversion transforms it into a "p". While children with good visual perceptual skills would experience no problems in learning to identify letter shapes, children who experience problems with the visual perception of letters would be greatly impaired in the acquisition of reading skills. Unfortunately, although confusions due to letter reversals provide an intuitively appealing explanation for the reading problems experienced by dyslexics, evidence indicates that reversal errors do not constitute a major source of reading difficulty for these children (Fischer, Liberman & Shankweiler, 1978; Richardson, 1984).

Many studies have failed to find such differences between competent and impaired readers. This failure may be due to the selection of an inappropriate measure of visual processing ability. In view of Seymour and Porpodas's (1980) observation that dyslexics appear to be *inefficient*, rather than *deficient,* in visual perception, tasks employed in any investigation of the potentially divergent visual skills of good and poor readers must be carefully selected. These tasks must be sufficiently complex to elicit differential performances from the two groups of readers, and preferably be of a fairly abstract nature to preclude the use of verbal labelling strategies which would provide the good readers with an immediate advantage (Mason & Katz, 1976; Mitchell, 1982). Indeed, of the investigations in the literature, those reporting differences between good and poor readers are the ones which have required the analysis of complex visual forms (Ruddock, 1990; Cornelissen *et al*, 1991; Eden *et al*, 1993).

3.4.2. Visual skills and reading competence: cause and effect?

The finding of good visual-perceptual skills in normal readers, and of visual-perceptual deficits in some dyslexic children, reveals nothing about the direction of causality between visual-perceptual skills and reading skills (Hulme, 1988; Bishop, 1989). Furthermore, the failure of many of the aforementioned studies to employ reading-age control children serves to preclude the drawing of conclusions concerning this relationship. Those that have included both chronological-age and reading-age matched control children report that dyslexics consistently display poorer visual sense than both the older and younger normal readers (Stein *et al*, 1987, 1988; Cornelissen *et al*, 1991). These findings are interpreted as arguing against suggestions that visual-perceptual disturbances are a *consequence* of poor reading skills (Vellutino, 1987). Instead it is proposed that young, normal, readers are aided in their reading development by *competent* visual abilities, whereas the reading skills of dyslexics are constrained by their *impaired* visual processing skills (Stein, 1991). Support for this suggestion has been offered in the form of training studies in which it is claimed that improving visual skills leads to an enhancement of reading ability (Masters, 1988; Stein, Riddell & Fowler, 1989). Such studies have been criticised, however, on the basis of their failure to adopt a double-blind paradigm and of the possibly fallacious interpretations placed on the findings (see Hulme, 1987; Bishop, 1989; Snowling, 1991). Thus, there appears to be a need for a carefully controlled longitudinal study of the development of visual skills. Such a study would enable an investigation of visual skills in children who eventually achieve reading competence and in those who fail to achieve age-appropriate literacy skills. This issue is addressed in **Chapters 6**, **7** and **8**.

3.4.3. Visual processing skills and reading competence: A summary

Although the sub-typing literature indicates that only a minority of dyslexics experiences reading problems *purely* related to deficient visual processing abilities (Hatchette & Evans, 1983; Seymour, 1986; Felton & Wood, 1989), the above evidence would suggest that a large number of dyslexics may suffer impairments in the processing of visual information at some level (Goulandris & Snowling, 1991; Lovegrove, 1993; Eden *et al*, 1993). The precise nature of these visual impairments remains to be determined. Rather than undertaking to highlight individuals with *purely linguistic* or *purely visual* deficits, it may be more informative in future studies to investigate the relative contributions of the two complementary aspects of processing in the dyslexic child (Lyon & Watson, 1981; Satz & Morris, 1981; Johnson & Zecker, 1991).

3.5. Conclusions:

On the basis of the above review it is apparent that differences between dyslexics and good readers, in terms of cognitive processing, are numerous. Tasks which require an awareness of the sounds of words and an ability to manipulate these sounds, tasks which place demands on phonological memory processes and tasks which require visual-perceptual competence have all been reported to present problems of varying degrees to different samples of dyslexic children (see **Section 3.1.3** for a discussion of the sub-typing literature). While there is universal agreement that the cognitive deficits which underlie these processing impairments are heavily implicated in dyslexics' reading problems, what is less clear is the prevalence and precise influence of each on the acquisition of literacy skills. This issue is addressed in **Chapters 7** and **8**. First, however, evidence of the neuropsychological profiles which underlie the cognitive processing abilities of normal readers and developmental dyslexics is discussed in **Chapter 4**.

~ CHAPTER 4 ~

The neuropsychology of lateralisation: Normal & abnormal aspects

4.1. Language representation in the normal brain

Modern notions of functional localisation of language date back to the middle of the 19th century when Broca (1861) and Dax (1865) reported examples of productive aphasia in patients who had exhibited frontal lesions of the left hemisphere. Later investigations by Wernicke (1874) extended this work by reporting a case of receptive aphasia which was associated with posterior left hemisphere lesions.

Since these early studies, increasingly sophisticated techniques have permitted a more comprehensive investigation of the areas in the brain thought to mediate aspects of language function. Electrical stimulation of the neocortex, Positron Emission Tomography (PET), Computerised Axial Tomography (CAT) and Magnetic Resonance Imaging (MRI), as well as traditional EEG, have all contributed to our understanding of language localisation in the brain. Electrical stimulation of the cortex of patients about to undergo surgery for intractable epilepsy, for example, has confirmed the importance of the anterior language area (corresponding to Broca's area), the posterior language area (located at Wernicke's area) and the supplementary language areas for the production and comprehension of language (Lesser, Luders, Morris, Dinner, Klem, Hahn & Harrison, 1986).

Although the exploratory techniques employed in early studies reveal a great deal about the cerebral localisation of language, their utility is rather limited in normal, intact subjects. The development of non-invasive neural imaging techniques capable of observing brain activity during linguistic processing in healthy individuals provides a more important and clear method of investigating language representations in the brain. One such technique, PET, measures the degree of cerebral metabolic activity and allows the observation of regional cerebral blood flow (rCBF) during linguistic and other types of processing in healthy, cerebrally-intact subjects. Petersen, Fox, Posner, Mintun & Raichle (1988), for example, took PET scans while subjects performed sensory, production or association language tasks. A bilateral increase in blood flow in the primary and secondary sensory areas was observed during the passive perception of words. Language production was associated with increased bilateral activation in the sensory and motor areas associated with the face, in addition to activation in the supplementary speech regions. During the performance of the association task blood flow increased in the left prefrontal cortex, especially in the left inferior region. Similarly, Price *et al* (1994) observed increased blood flow in the left inferior and middle frontal cortices during the performance of a lexical decision task and in the temporal region of the left hemisphere during reading (also reported by Wood, Flowers, Buchsbaum & Tallal, 1991; Flowers, Wood & Naylor, 1991). Research showing increased activation in the left frontal cortex in response to visually presented real words but not pseudowords, and also in the performance of semantic discrimination tasks, has also been interpreted as reflecting the localisation of semantic processing to this region (Petersen, Fox, Snyder & Raichle, 1990). Further evidence has shown increased activation in the left, medial extra striate visual cortex in response to proper and pseudo-words which obey the rules of English orthography (Petersen *et al*, 1990). No such activation resulted from the perception of nonsense letter strings, suggesting that the distinguishing of word-like from non word-like forms may be localised to the left, posterior extra striate cortex. The left hemisphere's temporal lobe - particularly the anterior and posterior fusiform gyri - is also implicated in the processing of visually and auditorily presented words as reflected in increased regional blood flow (Peterson *et al*, 1990; Nobre, Allison & McCarthy, 1994; Gur, Ragland, Resnick, Skolnick, Jaggi, Muenz & Gur, 1994).

While the development of PET techniques represents a great stride towards understanding the functioning of the brain in intact subjects, a number of factors limit their utilisation with intact *children.* One problem is the fact that this technique requires the injection of a radioactive isotope into the bloodstream for subsequent detection by means of their positron emissions. Although these isotopes are relatively short-lived, and presumably non-hazardous, the technique is nonetheless, invasive. A second factor inhibiting the use of PET techniques to monitor linguistic processing in children is the time scale involved. The half-lives of the radioactive isotopes employed are typically in the region of 20 to 30 minutes, thus the images are fairly slow to obtain. Perhaps the greatest problem with the use of the PET technique, however, is the means by which the positrons are detected. This requires the patient's head to be placed, perfectly still, into a scanner. The use of such a device would be stressful for a young child and it would also limit the type of behavioural task which could be employed (see Rose, 1992; Steinmetz & Seitz, 1991).

In view of the limitations of imaging techniques such as PET (and also of CAT and MRI: see Rose, 1992), electroencephalographic (EEG) measures would appear to offer an acceptable alternative for the investigation of functional lateralisation in intact children. The mechanisms involved in EEG recording, including the recording of event-related potentials (ERPs), are non-invasive, relatively naturalistic (enabling the performance of diverse behavioural tasks during the recording) and provide a virtual real-time representation of the functioning of the brain. These techniques provide a valuable means of investigating the neurophysiology underlying reading development in children. In fact, the use of such measures has served to reiterate the importance of the left hemisphere for the processing of linguistic stimuli by normal subjects (Davidson, Chapman, Chapman & Henriques, 1990; see also Ray, 1990 and Segalowitz & Berge, 1995 for reviews). Hemispheric lateralisation for language as indexed by ERPs is discussed in detail in **Section 4.4.4.**

In addition to their utility with normal subjects, neural imaging techniques have been employed to observe language functioning in 'abnormal' samples, such as those with specific learning difficulties. The importance of these techniques lies in the possibility that differences in reading or language production ability may be able to manifest themselves in different forms of brain activity or structure, i.e. the brains of normal and dyslexic children may show different patterns of cerebral activation or architecture. The evidence for this assumption is considered below.

4.2. Language representation in the dyslexic brain

Samuel Orton (1925) was the first to hypothesise a relationship between anomalous cerebral lateralisation of language functions and reading impairments, arguing that delayed neurological development was responsible for a failure of the left hemisphere to develop the expected "unilateral linguistic superiority" over the right hemisphere. This inhibition of 'normal' cerebral (i.e. left hemisphere) dominance was thought to be responsible for the difficulty in distinguishing mirror images (i.e. the letters "b" and "d"). This phenomenon Orton called "strephosymbolia" ("twisted symbols"). Although subsequent research has shown Orton's early theories to be rather misguided and oversimplified, they nonetheless appear to be fundamentally correct in their suggestion that dyslexia is in some way associated with anomalous cerebral lateralisation.

Neuropsychological evidence suggests that developmental dyslexia may be associated with reduced or delayed left hemisphere specialisation for the processing of language (Larsen *et al*, 1990; Galaburda *et al*, 1994). Structural measures, for example, indicate that dyslexics are more likely than normal readers to display symmetry in the region of the planum temporale (Larsen *et al*, 1990; Kushch, Gross-Glenn, Jallad, Lubs, Rabin, Feldman & Duara, 1993; Galaburda *et al*, 1994) and in the posterior regions of the brain (Tallal & Katz, 1989; Hynd & Semrud-Clikeman, 1989); they are also more likely to display reversed asymmetry in the parieto-occipital region (Rosenberger & Hier, 1980). It is possible that these findings may indicate a reduction in the normal left hemisphere superiority for the processing of verbal information in dyslexics (Hynd, Semrud-Clickman, Lorys, Novey & Eliopolos, 1990). This is also suggested by Bishop (1990), who observed that in dyslexics, "the left cerebral hemisphere is poorly developed and provides an inadequate substrate for development of competence in verbally based skills". The alternative possibility, that anomalous physiology in dyslexic brains is the result of an over-development of the right hemisphere, is considered below. Either of these possibilities would indicate that the development of cortical lateralisation is a key biological substrate in the acquisition of reading (Bryden, 1988; Larsen *et al*, 1990; Annett, 1992a). This is to be explored through the studies reported in the present thesis.

Post-mortem examinations have also revealed structural differences between the brains of good and impaired readers. High concentrations of microdysgenesis ("disorganised islands of cortex") have been observed, for example, in the left temporo-parietal regions of dyslexics' brains. Once again, this is notably in the region of the planum temporale (Galaburda, Sherman, Rosen, Aboitiz & Geschwind, 1985; Kaufman & Galaburda, 1989; Duane, 1989). Although such clusters are not unknown in the brains of normal readers, they are rare, and generally occur in the right anterior temporal cortex (Kaufmann & Galaburda, 1989). The effects of these microdysgeneses are twofold. Firstly, they seriously disturb the normal pattern of architecture in the brains of the dyslexics, and secondly, they remove the asymmetry which is normally observed between the enlarged language areas of the left temporo-parietal region and the smaller homologous areas of the right hemisphere (Galaburda *et al*, 1985). In humans the capacity for language is generally correlated with a significant development in the magnitude of the left temporo-parietal region and an attrition of neurons in the right hemisphere, casualties of "programmed cell death" (Ellis, Yuan & Horowitz, 1991; Brown, Hulme, Hyland & Mitchell, 1994). This combination produces the observed asymmetry between corresponding areas in the left and right hemispheres (Geschwind & Levitsky, 1968).

In view of the linguistic impairments and the cortical symmetry which characterise dyslexia, it might be logically inferred that the cognitive impairments experienced by dyslexics are the result of a developmental failure of the left hemisphere. This is not necessarily true, however. Physiological symmetries observed in dyslexics' brains, for example, are not the result of smaller than expected left hemisphere regions but of abnormally large cortical regions in the right hemisphere (Galaburda *et al*, 1985; Kaufman & Galaburda, 1989). It has been suggested that this symmetry may be due to the unexpected survival of neurons in the right hemisphere - a failure of the "programmed cell death" mentioned previously (Ellis *et al*, 1991; Brown *et al*, 1994) - having been used to support the left hemisphere's language processing functions (Hermann & Zeevi, 1991).

Clinical evidence of neurological abnormalities in the brains of dyslexics has also implicated bilateral involvement in the disruption of cerebral lateralisation. Bilateral lesions occurring during prenatal or postnatal development, for example, would prevent hemispheric reorganisation, resulting in permanently impaired linguistic processing (Kinsbourne & Hiscock, 1977, 1983; Satz, 1991). Even in the absence of overt lesions, cytoarchitectonic abnormalities have been observed in dyslexic brains (Galaburda & Eidelberg, 1982; Galaburda *et al*, 1985; Galaburda, 1986). These abnormalities, believed to be the result of a disruption in neuronal migration during a critical stage of foetal development (between the fifth and seventh gestational months), have manifested in the anterior cortex of both cerebral hemispheres (Galaburda *et al*, 1985), in the superior posterior temporal region of the left hemisphere (Galaburda *et al*, 1985) and in regions of the right temporal lobe (Drake, 1968). Conclusions based on the observation of cytoarchitectonic abnormalities must be drawn with caution, however, considering the number of subjects involved (N = 6 in total for these studies), the failure to include a control group, and the fact that dyslexic brains arriving at post-mortem are rarely perfectly healthy. Of Galaburda *et al*'s (1985) four dyslexics, for example, one was also epileptic and another had paroxysmal slowing of EEG, either of which could have accounted for the observed abnormalities.

4.3. The ontogeny of hemispheric lateralisation in the dyslexic brain

Since first suggestions of a relationship between anomalous cerebral lateralisation and reading impairments numerous researchers have attempted to identify the physiological bases of developmental dyslexia (Geschwind & Behan, 1982; Corballis, 1983; Kershner, 1985; Wyngaarden, 1987). Theories can generally be classified as involving either a "maturational lag" in the development of hemispheric specialisation or a "biological predisposition" to anomalous lateralisation. In view of the fact that, "volumes summarizing the research in this area have been written" (Hynd, Marshall, Hall & Edmonds, 1995), the present review will attempt merely to summarise the major findings and theories. The interested reader is directed to a number of recent, comprehensive reviews of this area (Hynd *et al*, 1995; Boliek & Obrzut, 1995; Hiscock & Kinsbourne, 1995; Segalowitz & Berge, 1995).

4.3.1 Maturational lag hypotheses of dyslexia I: Lenneberg's (1967) hypothesis

The earliest suggestion of a neuro-maturational lag in the brains of dyslexics was proposed by Lenneberg (1967) and subsequently adopted by Satz and Sparrow (1970). It was argued that although at birth the brain is equipotential (i.e. the two hemispheres are "functionally equivalent" (Lenneberg, 1967)) for the processing of language, one hemisphere (usually the left) becomes dominant over time. A delay in this developmental lateralisation is believed to account for the reading difficulties experienced by some children. Support for this hypothesis derives from studies reporting, for example, greater mixed handedness in 7 than in 9 year old dyslexics (Harris, 1957), a greater verbal dichotic right ear advantage in 12 year old normal readers than in dyslexic children of the same age (Satz, Rardin & Ross, 1971; see **Section 4.4.2**) and from reports of generally poorer motor performance in dyslexics than in age-matched controls, indicating neuromotor immaturity in the poor readers (Rutter, Tizard & Whitmore, 1970; Naidoo; 1972; Wolff, Cohen & Drake, 1984).

4.3.2. Maturational lag hypotheses of dyslexia II: Bakker's (1992) balance model:

A variation on the developmental-lag hypothesis of dyslexia is the "balance model" proposed by Bakker and colleagues (Bakker, Smink and Reitsma, 1973; Bakker, 1979; 1992). According to this theory the early stages of reading development (depending largely on perceptual discrimination) evoke predominantly right hemisphere processing, whereas final, competent, reading comes to depend on left hemisphere processing of syntactic and semantic information. Abnormalities in this developmental swing from right hemisphere to left, however, have been held accountable for the reading difficulties of developmental dyslexics. According to this model children who fail to progress beyond the right hemisphere mediation of linguistic processing will remain fixed at the perceptual level of textual processing (P-type dyslexics); in contrast, children who fail to initially adopt right hemisphere processing strategies, or who shift over to a reliance on left hemisphere strategies too early (L-type dyslexics) will disregard perceptual features of the text and will tend to produce substantive reading errors (i.e. the omission, addition or replacement of letters and words).

4.3.3. A critique of maturational lag models:

Although these hypotheses of the biological substrate of dyslexia have received some empirical support, the underlying assumption on which they are based (that neurological functions become progressively more lateralised with age), is questionable. Considerable neuropsychological evidence, for example, suggests that lateralised processing of linguistic stimuli occurs from infancy, possibly even from birth (Duvelleroy-Hommet, Gillet, Billard, Loisel, Barthez, Santini & Autret, 1995; Mehler & Christophe, 1995), with little evidence of increasing lateralisation thereafter (Obrzut, Hynd, Obrzut & Pirozzolo, 1981; Bryden, 1982; Bryden & Saxby, 1986). Of course, it is possible that whereas lateralisation may *normally* be present from birth this may not be the case in dyslexic brains.

In defence of such models, however, it has been argued that rather than referring to an initial state of functional symmetry the term equipotentiality instead indicates "the capacity of structures in the intact right hemisphere, (and) also the left hemisphere, to subserve speech and language functions after perturbations to the left hemisphere" (Satz, Strauss & Whitaker,1990; Satz, 1991). Support for this definition derives from the observation that language may be recovered following brain damage in infancy (prior to the age of 2 years, for example), whereas similar damage after the age of 6 years results in loss of certain language processing abilities (Rasmussen & Milner, 1977; Satz, Strauss, Wada & Orsini, 1988).

More recently maturational lag hypotheses of dyslexia have been redefined according to Luria's (1973) theory of the dynamic progression of lateralised function (Satz *et al*, 1990). Rather than suggesting that cognitive functions are initially represented bilaterally, gradually becoming lateralised to one hemisphere as the child matures, *progressive lateralisation* models accept that the functions of the left and right hemispheres are "structurally pre-programmed" but that maturational changes take place intra-hemispherically; these changes occur in an anterior-posterior progression through early childhood (Satz *et al*, 1990). Empirical support is provided by post-mortem and clinical findings of varying degrees of sparing and recovery of linguistic functions following brain injury at different stages of a child's development (Campbell & Whitaker, 1986; Satz *et al*, 1990; Satz, 1991). In view of these reformulations of progressive lateralisation theories of cortical development, differential rates of antero-posterior progressions may underlie the linguistic abilities of normal and reading-impaired children (Boliek & Obrzut, 1995).

4.3.4. Biological pre-disposition hypotheses of dyslexia:

Alternative theories of dyslexia have focused on a biological predisposition to anomalous lateralisation, based on the premise that some sort of pre-natal or early post-natal dysfunction in the development of the central nervous system results in anomalous structural and functional hemispheric organisation.

4.3.5. Biological pre-disposition hypotheses of dyslexia I: the testosterone hypothesis:

One such theory (Geschwind & Behan, 1982; Geschwind & Galaburda, 1985, 1987) suggests that abnormal cerebral development in developmental dyslexics may result from hormonal influences during pre-natal neurological development. Specifically, they propose that an excess of foetal testosterone retards left hemisphere development, allowing the right hemisphere to develop to a greater degree than the left. This enhancement of the right hemisphere is thought to increase the probability of sinistrality and also developmental disorders, including dyslexia. Although this theory would appear to account for the raised incidence of dyslexia amongst males, and of the increased likelihood of language disorders in sinistrals than in dextrals (Porac & Coren, 1981; see **Section 4.4.1 (b)**), it has been widely criticised and accused of 'obscuring rather than clarifying' (Annett, 1994) the relationship between handedness, sex differences and developmental dyslexia. The major criticisms of the hypothesis are considered briefly below.

The main premise of the testosterone hypothesis is the assumption of a "standard dominance pattern" in the majority of the population; this pattern represents the strong left hemisphere mediation of language and handedness and the strong right hemisphere dominance for non-linguistic functions. Any deviation from this pattern is considered by the model to represent "anomalous dominance". Unfortunately, even at this fundamental level the model has been criticised. No attempt is made, for example, to specify the mechanisms by which this typical pattern of cerebral asymmetry arises (see Annett, 1994). Furthermore, the assumption that dominance is a dichotomous state is criticised in that according to this belief any pattern of weak, but otherwise 'normal', lateralisation would be considered to be anomalous. On this basis, it is argued, the majority of the population would be so classified (Bryden, McManus & Bulman-Fleming, 1994).

The model is also open to criticism at an empirical level. For example, contrary to expectations on the basis of this theory, normal verbal IQ, handedness and cerebral functional lateralisation have been found in individuals with adrenogenital syndrome, characterised by high levels of pre-natal testosterone (Cappa, Loche, Borrelli & Pintor, 1988). Evidence is also reported of an association between increased pre-natal testosterone and strong dextrality in girls (Grimshaw, Bryden & Finnegan, 1993). Thus, the suggestion that high levels of testosterone retard development of the left hemisphere in foetuses is questionable (Pennington, Smith, Kimberling, Green, Marshall & Haith, 1987). In fact, a recent comprehensive review of this association between anomalous development, handedness and testosterone level found empirical evidence for the theory distinctly lacking (Bryden *et al*, 1994; see also Annett, 1994; Friedmann & Grodzinsky, 1994).

4.3.6. Biological pre-disposition hypotheses of dyslexia II: anomalous representation of visuo-spatial functions

A second biological theory suggests that, whereas both dyslexic and normal readers are lateralised to the left hemisphere for the mediation of linguistic processing, dyslexics are also considered to have bilateral spatial representations; this is thought to produce a pattern of cerebral organisation which may be viewed as essentially "two right hemispheres and none left" (Witelson, 1976, 1977; also Dalby & Gibson, 1981). According to this hypothesis excessive demands on the left hemisphere, to mediate both linguistic and spatial processing, may lead to reduced efficiency of linguistic processing in dyslexics. In spite of the intuitive appeal of this theory, however, a number of methodological and interpretational artefacts remain unaccounted for and supportive evidence is generally sparse (see Beaton, 1985).

4.3.7. Biological pre-disposition hypotheses of dyslexia III: Annett's right shift hypothesis

The "right shift" theory of Annett (1975, 1985, 1992a) may account for the conceptual link between cerebral lateralisation and reading ability. This theory suggests that chance is the major determinant of which hemisphere mediates language. A secondary influence is that imposed by a gene (RS+), the presence of which bestows an advantage on the left hemisphere for the processing of language. This left hemisphere bias also serves to increase the probability of right handedness, but it is not *sufficient* to guarantee dextrality (the implications of the right shift theory for handedness are discussed further in **Section 4.4.1 (b)**). With respect to developmental disorders, this theory suggests that individuals lacking this gene (RS-) are at risk for language and reading problems (including poor phonological processing skills) because they lack a boost to left hemisphere speech development. Thus, no attempt is made to suggest that the absence of the right shift gene is responsible for dyslexia, whereas the presence of the gene enhances the normal development of language. The right shift theory is able to account for the increased likelihood of non-dextrality in reading-impaired samples and for the persistence of dyslexics' linguistic processing difficulties into adulthood. Thus, it is a viable model of the relationship between cerebral lateralisation and the different facets of linguistic competence. The claims of this hypothesis will be considered in the present thesis in interpreting the handedness and language lateralisation data obtained from the good and poor readers in the cross-sectional studies (**Chapters 7 and 8**).

4.4. Behavioural and electrophysiological measures of cerebral lateralisation:

Studies documenting variability in cerebral lateralisation, and in behavioural asymmetries as they relate to literacy, typically compare good and poor readers on tasks involving lateralised responses. Tasks have included those of manual dexterity (Annett & Manning, 1990a; Brunswick & Rippon, 1994; Moore, Brown, Markee, Theberge & Zvi, 1995), dichotic listening (Bryden, 1988; Kershner & Morton, 1990; Kershner & Micallef, 1991) or the reporting of stimuli perceived in divided visual fields (Jones & Michie, 1986; Broman *et al*, 1986).

Electrophysiological measures are also increasingly being employed to provide a means of observing the activation of the brain during the performance of such tasks (Wood *et al*, 1991; Duncan, Rumsey, Wilkniss, Denckla, Hamburger & Odou-Potkin, 1994; Brunswick & Rippon, 1994). Observed differences are subsequently interpreted in terms of the differential reading abilities of the subject groups.

The remainder of the present review will consider some of the most commonly employed measures of lateralisation - handedness, dichotic listening and electroencephalography - and examine their utility to reading research. The potential of these measures to reveal any cerebral differences between competent and poor readers will also be considered.

4.4.1. Handedness:

4.4.1 (a) Handedness as a simple index of language lateralisation

It is acknowledged that handedness and language lateralisation are not mutually dependent. Language ability is unilaterally represented in the left hemisphere of 95% of right handers and 70% of left handers. Of the remaining 30% of left handers, 15% display right hemisphere language functioning and the other 15% have bilateral language representations (Segalowitz & Bryden, 1983; Peters, 1995). There appears to be a clear dissociation between the hemisphere responsible for controlling the dominant hand and the hemisphere responsible for the mediation of linguistic processing. Although a vast amount of research has been concerned with the psychophysiology of handedness and cerebral localisation of function (Galaburda, 1995; Boliek & Obrzut, 1995; Segalowitz & Berge, 1995), relatively little is known about the phylogeny (Lewis & Diamond, 1995) and ontogeny (Satz *et al*, 1990) of the relationship between these two variables (see Hiscock & Kinsbourne, 1995 and Peters, 1995 for reviews).

While the *direction* of hand dominance may reveal little about the underlying cerebral lateralisation (Annett, 1991) the *strength* of this dominance (i.e. the magnitude of between-hand differences in skill) is important for the purpose of investigating the relationship between hemispheric localisation of function and handedness (Annett, 1985, 1992a; Annett & Manning, 1990b; Brunswick & Rippon, 1993, 1994). Evidence indicates a greater involvement of the left than the right hemisphere in the execution of controlled sequential motor movements (Kolb & Milner, 1981; see also Beaton, 1985). Thus, disturbances in left and right hand performance on 'experience-neutral' motor tasks provide an indication of underlying dysfunction in (left hemisphere) motor function (Bishop, 1984). Although it is not suggested that lateral asymmetry is causally related to localisation of hemispheric language functions, the fact that the left hemisphere also subsumes responsibility for the mediation of linguistic processing in the majority of individuals suggests that the former will provide a reflection of the latter (Annett & Kilshaw, 1984; Strauss, Gaddes & Wada, 1987; Annett, 1991). The implications of this relationship with regards to reading ability are discussed below (**Section 4.4.1 (b)**).

Investigations of the relationship between handedness and language development in infants have revealed a "temporal linkage" between the two (Peters, 1983) such that the development of handedness fluctuates depending on the degree to which language development interferes with the use of the dominant hand (Bates, O'Connell, Vaid, Sledge & Oakes, 1986). Discontinuities in the emergence of manual preference should coincide, therefore, with stages of language development (Ramsay, 1985), possibly due to "the proximity of these two control processes in 'functional cerebral space'" (Kinsbourne & Hicks, 1978). These studies have generally involved the testing of infants during early language acquisition. No comparable study has been undertaken to investigate the relationship between handedness and lateralisation during the period of early reading acquisition, however, an omission which is directly addressed in **Chapter 5**.

4.4.1 (b) Handedness and reading ability

If dyslexia *were* found to be the result of anomalous cerebral lateralisation, this *may* be reflected in the handedness of the dyslexic. Porac and Coren (1981), for example, observed that "samples of poor readers are never found to be more dextral, more consistent or more congruent in their lateral preference patterns than average or good readers. Thus the literature suggests...that shifts away from consistent and congruent dextrality can be associated with reading impairment".

The picture is not this clear, however. Over the years reading disabilities have been associated with strong sinistrality (Geschwind & Behan, 1982, 1984; Annett & Manning, 1990b), with mixed handedness (Orton, 1937; Harris, 1957), with strong dextrality (Annett & Kilshaw, 1984; Annett & Manning, 1990b), with a lack of strong right-handedness (Schachter, Ransil, & Geschwind, 1987) and with no particular lateralised preference (Neils & Aram, 1986; Bishop, 1990). Two explanations for the multifariousness of these findings have been offered. Firstly, while there may be no relationship between reading ability and laterality amongst the population at large, samples of children with specific reading impairments are reported to be likely to include greater than expected numbers of non-dextrals (Annett & Turner, 1974; Benton, 1975). Secondly, the criteria used to assess handedness differ from study to study. Measures of handedness include self report, handedness questionnaires, the performance of a sequence of skilled activities with each hand, and use of simple unimanual skill tasks. The variability in these assessment measures suggests a possible reason for the apparent inconsistencies found in behavioural studies (Peters, 1995; Hiscock & Kinsbourne, 1995).

An overview of this research is provided by Bishop's (1990) review of 20 such studies. Of the dyslexics in these studies 11.2% were sinistrals, compared with 5.8% of the controls. These mean values conceal more extreme levels of sinistrality reported amongst dyslexics. Geschwind and Behan (1982, 1984), for example, report that between 7-10.9% of sinistrals compared with only 0.3-1.2% of dextrals are prone to developmental language disorders. The incidences are generally below what would be expected, however, if weak cerebral lateralisation was a major factor in dyslexia. Furthermore, other researchers have failed to find any significant differences on measures of hand, leg or eye preference between children with severe language problems and control children matched for intelligence, socio-economic status and age (Johnston, Stark, Mellits & Tallal, 1981; Neils & Aram, 1986; Bishop, 1990). Unfortunately a general failure amongst many lateralisation studies to distinguish between sub-groups of non-right-handers may obscure links between handedness and developmental dyslexia (Annett & Kilshaw, 1984; Annett & Manning, 1990b; Annett, 1991). On the basis of such evidence Bishop concludes that a causal link between anomalous laterality and dyslexia is highly improbable. This conclusion has been questioned by Eglinton and Annett (1994). They argued that Bishop's (1990) finding of significantly more non-dextral dyslexics than controls, which she dismissed as 'too small for further consideration', is precisely of the size predicted by the right shift theory (see below, also Annett, 1972, 1985). Eglinton and Annett (1994) subsequently re-analysed Bishop's (1990) data, allowing for different classifications of handedness across different studies, and reported small, but significant, numbers of non-dextrals amongst the dyslexics in line with the predictions of the right shift theory as outlined below.

According to the right shift theory (Annett, 1972, 1985) individuals at the left of the hand skill distribution (those who lack the RS+ gene) lack a boost to the development of language which normally accompanies left hemisphere specialisation; they also run a risk of speech and language processing difficulties, including those skills crucial for reading acquisition. On this basis the finding of poor phonological processing skills in children at the left of the handedness continuum is hardly surprising (Annett, 1992a). The observation that children at the right of the hand skill distribution are also at risk for poor intellectual development, including impaired reading (Annett & Kilshaw, 1984; Annett & Manning, 1990b) is unexpected, however. This finding has subsequently been explained such that a double dose of the right shift gene (RS++) serves not to boost the left hemisphere but to handicap the right hemisphere (Annett & Kilshaw, 1984; Annett, 1991). An over-reliance on the left hemisphere for verbal and visuospatial processing impairs both (Annett & Manning, 1989, 1990b).

These studies highlight the importance of handedness, not just in terms of basic dichotomy but as a continuum, as a factor which cannot be overlooked in an investigation of normal and abnormal reading development.

4.4.2. Dichotic listening:

4.4.2 (a) The utility of dichotic listening as an experimental neuropsychological index of lateralisation:

A second commonly used measure of laterality involves the simultaneous presentation of speech sounds to the two ears for the subject to report. These sounds are usually either consonant-vowel (CV) pairs (Ahonniska, Cantell, Tolvanen & Lyytinen, 1993; Clarke, Lufkin & Zaidel, 1993; Brunswick & Rippon, 1994), or word/ digit pairs (Strauss *et al*, 1987; Tzavaras, Phocas, Kaprinis & Karavatos, 1993). Stimuli presented to the ear contra-lateral to the hemisphere responsible for the mediation of the processing of that particular type of stimulus tend to be reported with greater accuracy than those presented to the ipsi-lateral ear. The vital aspects appear to be hemispheric functional asymmetries in conjunction with physiological ear (auditory) asymmetries as outlined below (see also Efron, Crandall, Koss, Divenyi & Yund, 1983; Connolly, 1985). This usually results in a right ear advantage (REA) for the reporting of verbal stimuli and a left ear advantage (LEA) for reporting non-verbal sounds (Mondor & Bryden, 1991; Ahonniska *et al*, 1993; Duvelleroy-Hommet *et al*, 1995).

The observation of stimulus-specific ear advantages in dichotic listening studies is dependent on a number of basic premises: (1) the left and right hemispheres of dextrals are specialised for verbal and non-verbal skills respectively (see Beaton, 1985; Galaburda, 1995; Mehler & Christophe, 1995 for reviews of studies investigating the cerebral lateralisation of cognitive functions); (2) contra-lateral auditory pathways dominate over, and occlude, ipsi-lateral pathways. If the auditory pathways running from the two ears to the temporal lobes were "cognitively" equivalent, then irrespective of the specialised nature of the stimulus, no ear advantage would emerge (Price, Wise, Ramsay, Friston, Howard, Patterson & Frackowiak, 1992; Hugdahl, 1995); (3) in instances of differential stimulation the left hemisphere selectively attends to information in the right side of perceptual space (Bryden, 1970; Hiscock & Kinsbourne, 1977, 1980); and (4) stimuli directed to the ipsi-lateral hemisphere must traverse the corpus callosum prior to processing by the dominant hemisphere (Bradshaw & Nettleton, 1988; Clarke *et al,* 1993).

4.4.2 (b) Dichotic listening and reading ability

In view of the evidence linking dyslexia with anomalous cerebral lateralisation it should follow that differences would be observable between the ear advantage indices of good and poor readers for the processing of dichotically presented verbal stimuli. The evidence is far from unambiguous, however. Mirroring the apparent inconsistency in handedness research, dichotic listening studies have variously produced verbal right ear advantages (REAs) for both impaired readers and chronological-age matched normal readers (Tzavaras, Kaprinis & Gatzoyas, 1981; Tzavaras *et al*, 1993; Kershner, Henninger & Cooke, 1984; Kershner, 1985), REAs for normals but not for dyslexics (Obrzut *et al*, 1985; Obrzut, Conrad & Boliek, 1989; Boliek, Obrzut & Shaw, 1988) and no REA for either group (Zurif & Carson, 1970; Hynd, Obrzut, Weed & Hynd, 1979) under different recall conditions. These patterns may suggest either that both normal and impaired readers process verbal information, as expected, in the left hemisphere, that dyslexics are less lateralised than normal readers (as previously hypothesised), or that both good and poor readers display inconsistent lateralisation. In many of these studies, however, the dyslexics tended to recall more of the stimuli presented to the left ear than did the controls; this may either indicate a slight bias amongst these children towards the right hemisphere for the processing of linguistic stimuli or an attentional bias towards the left ear. Such results have been interpreted as reflecting poor left hemisphere functioning in dyslexics (Witelson, 1976; see also Annett, 1985, 1992b).

Cross-sectional testing of dyslexic children and reading-age matched controls has revealed that dyslexic children display the same pattern of lateralisation as younger children without reading impairments (Bakker *et al*, 1973; Bakker, Teunissen & Bosch, 1976). This has been interpreted as reflecting a developmental increase in lateralisation which is in some way delayed in the reading disabled children. The logical corollary to this suggestion, that in time the dyslexics will achieve a "normal" pattern of cerebral lateralisation with a concomitant improvement in their reading skills, has yet to be demonstrated (see Fennell, Satz & Morris, 1983).

Dermody, Mackie & Katsch (1983), however, approached the problem from a slightly different angle, and tested 15 poor readers (the bottom quartile of a mainstream class) and 15 reading-age matched controls on a task involving the monaural or dichotic presentation of C-Vs. Both groups displayed an REA for the monaurally presented stimuli and performed at a similar level of accuracy. REAs were also observed in the dichotic condition although the control children performed with a greater degree of recall accuracy than the poor readers. These findings were interpreted as reflecting a specific recall deficit in the poor readers when attempting to recall items which occur in rapid succession, i.e. dichotically.

The finding of greater recall accuracy by normals than by dyslexic readers is not uncommon in the dichotic listening literature (see Hynd *et al* , 1979; Milberg, Whitman & Galpin, 1981; Tzavaras *et al*, 1993). This suggests that, irrespective of the pattern of cerebral lateralisation, dyslexics may be less efficient at processing the dichotic stimuli than are normal control children. This may be due to a combination of an impaired ability to separate information arriving through the two ears (Bryden & Allard, 1976), a poorer ability to filter out irrelevant information and a greater susceptibility to switch attention randomly between the two channels (Hynd *et al*, 1979).

This latter possibility has prompted a subtle modification of the dichotic listening paradigm as researchers have become increasingly interested in investigating the differential effects of selective attention on the dichotic performance of dyslexics and of normal readers (Obrzut, 1991; Mondor & Bryden, 1991; Kershner & Micallef, 1992). The directed attention recall procedure was introduced, therefore, into the traditional dichotic listening task (Hiscock & Kinsbourne, 1980; Obrzut *et al*, 1981; Obrzut, Hynd & Obrzut, 1983). This has been subsequently deemed to be "the most valid laterality measure for observing auditory receptive language and non language lateralisation in learning-disabled children" (Bryden, 1988; Obrzut, 1989; Boliek & Obrzut, 1995) -

4.4.2 (c) Directed attention studies

These studies have their conceptual origin in Kinsbourne's (1970, 1973, 1975) attentional model of functional asymmetry. This proposes that the type of stimulus presented "activates" the hemisphere best able to process it, thus bestowing an attentional advantage on the contra-lateral ear. By asking subjects to selectively report only stimuli perceived at a specified ear, while ignoring stimuli at the other ear, it is possible to control the subject's deployment of attention and thereby minimise artifactual attentional effects which are thought to contaminate free report studies (Morris, Bakker, Satz & Van der Vlught, 1984; Hiscock & Decter, 1988).

Directed attention dichotic listening tasks have revealed that in most normal dextral subjects, the verbal perceptual bias to the right side of space interacts with the underlying left hemisphere functional lateralisation to produce a right-sided attentional bias for verbal stimuli (Hiscock & Kinsbourne, 1980; Boliek *et al*, 1988). This interaction generally yields a consistent verbal REA regardless of the specified ear of report although the magnitude of the REA may be somewhat attenuated when attention is directed to the left ear (Murray, Allard & Bryden, 1988; Boliek *et al*, 1988; Bloch & Hellige, 1989). Thus it may be considered that a strong cerebral structure exists in normal individuals, in which the left hemisphere is "prewired" for the processing of verbal information and right hemisphere involvement in this processing is suppressed. Attentional strategies further serve to enhance this left hemisphere processing efficiency yielding a strong rightward attentional bias for the processing of linguistic information (Boliek *et al*, 1988).

The manipulation of attention in dichotic listening tasks has also been employed to further our understanding of cerebral functional organisation and attentional effects in children with reading impairments (see Obrzut, 1991; Boliek & Obrzut, 1995). These studies have yielded lateralised performance differences between good and impaired readers. During free recall and forced right ear response conditions dyslexics tend to demonstrate a verbal REA, as found in normal readers; when asked to selectively report verbal stimuli directed to the left ear, however, dyslexics have been found to display either an attenuated REA or an LEA (Boliek *et al*, 1988; Kershner & Micallef, 1992; Obrzut, Bryden & Boliek, 1992). While these results do not necessarily indicate that dyslexics' underlying cerebral structure is anomalously lateralised compared with that of normals (although this suggestion is not dismissed (Obrzut *et al*, 1985, 1989; Obrzut & Boliek, 1988)) it has been suggested that the structure is not as strong. The inability of the left hemisphere to suppress the involvement of the right hemisphere during the processing of verbal stimuli renders dyslexics more susceptible than normal readers to attentional influences (Hugdahl & Andersson, 1987; Boliek *et al*, 1988; Obrzut, 1991).

A possible source of this inability of the dominant hemisphere to suppress the non-dominant hemisphere is the corpus callosum, the primary function of which, evidence suggests, is the maintenance of a division of attention across perceptual space (Tweedy, Rinn & Springer, 1980). In commissurotomised patients, for example, the elimination of this balance removes the inhibitory control of the right hemisphere over the left which enhances the bias towards the right perceptual field; this results in an exaggerated right ear advantage (Zaidel, 1983; Musiek, Reeves & Baran, 1985; Clarke *et al*, 1993). It may be conjectured, therefore, that some inability of the dyslexic's corpus callosum to maintain the perceptual balance between the hemispheres may account both for the observed anomalous perceptual biases and also the generally poorer performance of dyslexics than controls on dichotic listening tasks (Obrzut *et al*, 1981, 1983). The relationship between callosal size and functional inter-hemispheric interaction, reflected in performance on phonological processing tasks, has already been demonstrated in normal subjects (Clarke *et al*, 1993). What remains to be demonstrated is a similar relationship between behavioural measures of linguistic processing and callosal functioning in dyslexics.

4.4.3. How valid are behavioural measures as indices of cerebral asymmetry?

In view of the inconsistency in the literature relating behavioural and neuropsychological measures of cerebral specialisation, the validity of indirect measures of functional lateralisation, such as dichotic listening, has been called into question (Shucard, Cummins & McGee, 1984; Segalowitz, 1986). Levels of agreement between objective and behavioural measures of cerebral language lateralisation are generally in the region of 80-97% (Strauss *et al*, 1987; Zatorre, 1989). Whereas techniques such as intracarotid amobarbital injections (Strauss *et al*, 1987; Zatorre, 1989) or unilateral electroconvulsive treatment (Geffen, Traub & Stierman, 1978; Geffen & Caudrey, 1981) assess speech production, the dichotic listening paradigm is a measure of lateralised speech perception (Jancke, Steinmetz & Volkmann, 1992). This dichotomising of linguistic functions serves to highlight a problem inherent in any study attempting to map cerebral linguistic dominance. Language is not a unitary phenomenon, so attempts to localise a single "linguistic device" may be regarded as futile (Studdert-Kennedy & Shankweiler, 1970; Jancke *et al*, 1992). That said, the dichotic listening task is still considered to provide a valuable non-invasive means of assessing hemispheric lateralisation in normal samples (Bryden, 1982; Annett, 1991; Boliek & Obrzut, 1995).

Before considering the psychophysiology of cerebral asymmetry and reading ability, it is worth pointing out that behavioural measures may not be capable of distinguishing between subtle degrees of lateralisation, including anteroposterior progressions which have been implicated in dyslexia (discussed in **Section 4.3.3**). In responding to this concern it must be borne in mind that observed differences in behavioural asymmetry should only be used to infer the *relative degree* of hemispheric asymmetry, to provide an attenuated "reflection" of asymmetric cerebral processing. The use of the dichotic listening technique for this purpose already has reported theoretical and empirical validity (Van de Vijver, Kok, Bakker & Bouma, 1984; Harper & Kraft, 1986). In investigating the more subtle, intra-hemispheric, changes in laterality researchers are increasingly employing psychophysiological measures (event-related potentials and neural imaging techniques, for example) in conjunction with established behavioural measures, such as dichotic listening. The hope is that by correlating the findings from each it may be possible to obtain a clearer insight into the neuropsychological bases of normal and abnormal reading development.

4.4.4. Event-Related Potentials:

The technique of measuring event-related potentials (ERPs) has been used widely to observe psychophysiological concomitants of reading and linguistic ability (Taylor, 1993; Mills, Coffey, Neville, 1993, 1994; Lovrich, Kazmerski, Cheng & Geisler, 1994). ERPs may be viewed as "time-locked" segments of electroencephalographic (EEG) activity which occur either in preparation for, or in response to, specific internal (endogenous) or external (exogenous) events (Cooper, Osselton & Shaw, 1980; Coles, Gratton & Fabiani, 1990). ERPs recorded at the scalp may be elicited by the presentation of stimuli in the visual, auditory or somatosensory modalities. Although it is not yet possible to establish unequivocally the neuronal generators responsible for scalp-recorded ERPs (see Allison, Wood & McCarthy, 1986; Vaughan & Arezzo, 1988; Coles *et al*, 1990), it is suggested that ERP components originate in the region of the primary cortical sensory areas (Goff, Allison & Vaughan, 1978). The auditory ERP, for example, has generators in the supratemporal plane of the auditory cortex (Scherg & Von Cramon, 1986; Vaughan & Arezzo, 1988), in the secondary auditory cortex (Simson, Vaughan & Ritter, 1977) and on the lateral surface of the temporal lobes (Celesia, 1976; McCallum & Curry, 1980). Evidence suggests that the visual ERP has an origin in the occipital region (Kavanagh, Darcey, Lehmann & Fender, 1978; Mangun & Hillyard, 1990). The origin of the movement-related potential has been localised to the motor areas of the cerebral cortex (Deecke, Weinberg & Brickett, 1982; Okada, Williamson & Kaufman, 1982).

In contrast to the background EEG signal individual ERPs may be too small to detect clearly, emerging as "mere zephyr(s) in the mental hurricane" (Fincher, 1984, p.143). Thus, single ERPs are normally indistinguishable from this background noise. The magnitude of the ERP increases, however, as a function of the number of successive presentations (N) of the evoking stimulus, while the EEG increases as a function of the square root of N. To enhance the 'stimulus-bound' aspects of the ERP, while averaging out the non-stimulus related activity - or background EEG - it is necessary to present a stimulus repeatedly. The production of an average evoked response according to the expression:

$$\frac{\text{ERP amplitude (N)}}{\text{EEG amplitude } (\sqrt{N})} = \frac{5\ \mu V\ (100)}{20\ \mu V\ (10)} = \frac{500}{200} = 2.50,$$

where a single ERP is 5 μV, the background EEG is 20 μV and N = 100 presentations, would yield an ERP two and a half times the size of the background EEG (Andreassi, 1989). The visibility of the ERP (the signal-to-noise ratio) increases proportionally with the number of stimulus presentations.

The peaks and troughs which comprise the ERP are labelled according to their polarity (P indicates a positive peak, N a negative trough) and their latency (100, 200, 300 milliseconds post-stimulus onset, for example - see Donchin, Callaway, Cooper, Desmedt, Goff, Hillyard & Sutton, 1977). Within this classification ERPs may be subdivided into their early-latency, middle-latency and late components (Donchin, Ritter & McCallum, 1978). The early-latency components (within 100 milliseconds of stimulation) are thought to reflect purely the activity of the sensory pathways that transmit signals from peripheral receptor sites to the central processing systems (Coles *et al*, 1990); the middle-latency ERP components (including the N100 and P200, negative and positive components occurring 100 and 200 milliseconds, respectively, post-stimulus presentation) are also considered to represent elementary feature analysis, including stimulus evaluation and classification (Parasuraman, Richer & Beatty, 1982; Lubar, Gross, Shively & Mann, 1990). In fact, Picton, Campbell, Baribeau-Braun & Proulx (1978) have suggested that the N100 "might reflect the activation of the processes necessary to the evaluation of incoming information". Also known as sensory potentials, exogenous components are influenced by the physical properties of the eliciting stimulus (Hillyard, Picton & Regan, 1978) and although these components precede cognitive processing it is expected that any differences in sensory perception between individuals would be reflected in these ERPs (see **Section 4.4.5** on the relationship between the N100, the P200 and reading ability).

In contrast to the early and middle latency components, the later components of the ERP are dependent upon the interaction between the individual and the eliciting event and are often associated with a subject's prior experiences, intentions and decisions (Hillyard & Kutas, 1983; Coles *et al*, 1990). These components (the P300, for example, a positive-going wave which occurs at approximately 300 milliseconds following stimulus presentation) occur at a relatively late stage following stimulus presentation and reflect cognitive processing, making them the focus of researchers investigating cognitive functioning (see **Section 4.4.7**).

4.4.5. Early sensory discrimination and the N100 - P200 components

Although the N100 and P200 components of the ERP tend to co-vary their independence is generally accepted. The N100 has been associated with early sensory-information processing while the P200 is thought to reflect the allocation of attentional resources, although relatively little is known about the psychological significance of this latter component (Vaughan, Ritter & Simson, 1983; Naatanen & Picton, 1987).

The amplitude of these sensory components may be influenced by two variables. First are the stimulus characteristics. Increases in temporal uncertainty (*when* a stimulus is presented) or event uncertainty (*which* stimulus is presented), for example, significantly increase the amplitude of these components (Schafer, Amochaev & Russell, 1981; Wastell, Kleinman & MacLean, 1982). Second, imposition of selective attention is important (see Naatanen, 1967, 1975); for example, when the rate of stimulus presentation is fairly rapid, the amplitude of the ERP is greater to attended than to unattended stimuli (Harter, Anllo-Vento & Wood, 1989; Alho, Woods & Algazi, 1994; Berman & Friedman, 1995).

A number of studies have related the amplitude of the N100 and P200 components recorded over the left and right cerebral hemispheres to the presumed localisation of function within that hemisphere (see Hillyard & Woods, 1979; Brown, Marsh & Ponsford, 1985). Studies involving the presentation of linguistic stimuli, for example, have reported larger amplitudes over the left than the right hemisphere (Papanicolaou, Eisenberg, & Levy, 1983; Van de Vijver *et al*, 1984). Furthermore, the left hemisphere focus of activation in response to linguistic stimuli has been observed from infancy through to adulthood with nonsense words (Segalowitz, Wagner & Menna, 1992), consonant-vowel (C-V) phonemes (Wood, Goff & Day, 1971; Wood *et al*, 1991), individual letters in a phonological oddity task (Taylor, 1993), natural speech as opposed to mechanical sound effects (Matsumiya, Tagliasco, Lombroso & Goodglass, 1972; Hillyard & Woods, 1979) and rhyming words in a poem (Hillyard & Woods, 1979).

Interpretational problems beset such findings, however. Firstly, homologous generators in the two hemispheres may be differentially located; the left and right hemisphere auditory cortices, for example, are asymmetric in size (Galaburda, Sanides & Geschwind, 1978). Thus, differences in electroencephalographic activation recorded at the scalp may reflect differential underlying physiology rather than differential patterns of hemispheric activation *per se*. Secondly, the amplitude recorded over each hemisphere in response to auditory stimulation may be a function of the ear stimulated. Amplitudes are typically larger and latencies shorter over the hemisphere contra-lateral to the ear of stimulation than over the ipsi-lateral hemisphere (Connolly, 1985; Alho *et al*, 1994). These effects have been explained in terms of the stronger, faster and more numerous contra-lateral than ipsi-lateral auditory pathways, leading to better representation of stimuli at the contra-lateral auditory cortex (Kimura, 1967). There are methodological irregularities, however, such as the use of a single active electrode (Butler, Keidel & Spreng, 1969), the failure to reference the active electrodes to an inactive recording site (Majkowski, Bochenek, Bochenek, Knapik-Fijalkowsa & Kopec, 1971), and the presentation of non-random, non-linguistic stimuli (Andreassi, DeSimone, Friend & Grota, 1975). In spite of these problems, it *is* always possible that differential amplitudes recorded over the two hemispheres *actually* reflect greater levels of sensory processing in one hemisphere than in the other (Naatanen & Picton, 1987). This possibility is discussed in the next section.

4.4.6. Variations in the N100 - P200 ERP components as a function of reading ability

Many experimental paradigms have been employed to investigate potential differences in the perceptual abilities of good and impaired readers. One of the earliest studies reported finding N200 amplitude attenuation over the parietal region of the left hemisphere in response to flashes of lights, with the degree of attenuation related to the degree of reading impairment (Conners, 1971). No control group was employed in this study, however, thus limiting its usefulness. Attempts at replicating this study, using matched control children have been not entirely successful. Preston, Guthrie & Childs (1974), for example, presented disabled readers and control children with either light flashes or with brief exposure to the word "cat". In apparent support of Conners's (1971) finding, Preston *et al* report smaller ERPs over the left parietal region in the impaired readers than in the normal readers. These results were interpreted as indicating poorer stimulus processing abilities of the impaired readers although attentional effects were not considered and no comparison was made of amplitudes recorded from the left and right hemispheres within the groups.

Similar ERP paradigms have subsequently been found to elicit a number of different results including: (1) no auditory or visual ERP amplitude asymmetries in either reading-impaired or control children and no attenuation of the response recorded from the left hemisphere in the former group of children (Weber & Omenn, 1977); (2) larger P140-N200 amplitude responses over the right hemisphere parietal and occipital regions in both control and impaired readers, although this increase was greater for the poor readers than for the controls (Sobotka & May, 1977); and (3) significant between-group differences in response to target stimuli such that reading-impaired children displayed the greater amplitude visual ERPs, especially over the contra-lateral occipital region; no between-group differences were found in response to non-target stimuli (Harter *et al*, 1989).

Rather more reading-relevant stimuli - visually presented words - have also been employed to examine the differential processing abilities of good and poor readers. Such studies have yielded larger differences in ERP amplitude to words and light flashes in the left parietal region of the brain in control subjects as compared with poor readers (Preston, Guthrie, Kirsch, Gertman & Childs, 1977). Control readers have also been found to exhibit larger amplitude N200 in the left hemisphere's parietal region than dyslexics, in response to words flashed on a screen (Symann-Louett, Gascon, Matsumiya & Lombroso, 1977). Longer ERP latencies, indicating slower stimulus processing, have been reported for poor readers (Symann-Louett *et al*, 1977; Weber & Omenn, 1977; Harter *et al*, 1989). Other studies have not found longer latencies (Sobotka & May, 1977; Sutton, Whitton, Topa & Moldofsky, 1986).

More recent studies examining inter-hemispheric differences between good and poor readers, in response to visual and auditory stimuli, have reported evidence of greater symmetry in ERP amplitude (Cohen & Breslin, 1984; Brunswick & Rippon, 1994) and latency (Sutton *et al*, 1986) in poor readers than in controls. This may indicate a lesser degree of hemispheric specialisation in the dyslexics. Different patterns of asymmetry have also been found in the two groups, with dyslexics exhibiting a pattern of ERP responses commensurate with a lesser involvement of the left hemisphere in linguistic processing than that seen in control readers (Shucard *et al*, 1984; Landwehrmeyer, Gerling & Wallesch, 1990). The general failure to find hemispheric differentiation amongst the poor readers may be taken in support of hypotheses linking dyslexia with reduced or delayed left hemisphere specialisation for the processing of linguistic stimuli.

Although many early ERP studies of good and poor reading focused largely on the early sensory components of the waveform, more recently attention has shifted to the later components, i.e., the P300, described by Barrett (1993) as "the thinking person's evoked-potential" (see also Ciesielski, 1989; Taylor & Keenan, 1990; Duncan *et al*, 1994).

4.4.7. Cognitive processing and the P300

The P300 component of the ERP is a modality-independent wave which reflects cognitive processing (Donchin *et al*, 1978; Donchin & Coles, 1988). It is commonly elicited in response to an "oddball" paradigm in which subjects are required to detect, or in some way respond to, infrequent target stimuli (usually comprising 25% of presentations) interspersed with frequent non-target stimuli (Sutton, Braren, Zubin & John, 1965); its occurrence accompanies the detection of the target stimulus (Cooper *et al*, 1980).

The amplitude of the P300 is influenced by a variety of factors, including (1) the subjective probability of the stimulus; the two are inversely related (Donchin, Karis, Bashore, Coles & Gratton, 1986; Polich, 1987); (2) the relevance of the stimulus to the subject's performance of the task, i.e. the presentation of rare and frequent tones whilst a subject performs a primary task will not elicit a P300 (Israel, Chesney, Wickens & Donchin, 1980; Bosco, Gratton, Kramer, Wickens, Coles & Donchin, 1986), and (3) task difficulty, such that the greater the processing demands of the task the smaller the P300 response to any distractory stimulus (Donchin, Kramer & Wickens, 1986). In fact, Johnson (1986, 1992) has suggested a "triarchic" model of P300 amplitude variance, in which the improbability of the stimulus (subjective expectancies) and the meaning of the stimulus (the complexity of the task, the complexity of the stimulus and the importance of detecting the stimulus) are added together and multiplied by a "transfer" factor (the amount of attention paid to the task by the individual). The P300 appears, therefore, to be the electrophysiological manifestation of a combination of underlying processes.

The latency of this component may also be manipulated by experimental factors. On the basis that P300 amplitude varies according to stimulus probability, it follows that some initial evaluation of the stimulus must occur prior to the occurrence of the P300; thus latency is thought to reflect the speed, and ease, of stimulus categorisation (Desmedt & Debecker, 1979; Pritchard, 1981).

Speculation about the functional significance of the P300 has lead to suggestions that it reflects a process of "context updating". The presentation of an unexpected event or stimulus demands an updating of representations in working memory if the individual is to maintain an accurate representation of its environment. It is this updating process which is thought to be reflected in the appearance of the P300 (Klein, Coles & Donchin, 1984; Donchin & Coles, 1988).

4.4.8. Variations in the P300 as a function of reading ability

Dyslexics have been found to exhibit smaller amplitude and longer latency P300s than normal readers (Ollo & Squires, 1985; Finley, Faux, Hutcheson & Amstutz, 1985; Taylor & Keenan, 1990). Surprisingly, these effects are found not only during the processing of linguistic stimuli (letters, words and nonsense words) but also during non-linguistic processing, during the discrimination of simple visual shapes, for example (Taylor & Keenan, 1990; See **Section 3.4** for a discussion of the role of visual perceptual factors in developmental dyslexia). In view of the aforementioned relationship between task difficulty and the characteristics of the P300 (**Section 4.4.7**), these findings have been interpreted as supporting suggestions that dyslexic children experience greater difficulty than normal readers in various aspects of cognitive processing.

Evidence regarding inter-hemispheric differences between children of varying literacy capabilities is less clear. Johnstone, Galin, Fein, Yingling, Herron & Marcus (1984) and Taylor & Keenan (1990), for example, found greater left than right hemisphere amplitudes in both good and poor readers during the processing of linguistic stimuli, i.e. they observed no evidence of lateralised differences between the children. Shucard *et al* (1984) reported smaller amplitude ERPs in the right hemisphere than in the left in poor readers but the opposite pattern in good readers in response to reading-related tasks. This apparently paradoxical pattern of results was interpreted as indicating a greater reliance on left hemisphere processing by the reading-impaired children than by normal readers. This suggestion stands in contrast to the findings of Johnstone *et al* (1984) who, in a further study, observed a lesser involvement of the left hemisphere in the processing of linguistic stimuli in reading-impaired than in normal children. Other researchers have reported no inter-hemispheric differences in ERP activation in developmental dyslexics during the processing of verbal and non-verbal stimuli (Chayo-Dichy & Ostrosky-Sollis, 1990).

In addition to the diverse behavioural measures employed in the different studies it is possible that the lack of a universally agreed-upon criterion for the identification of developmental dyslexia (**Section 3.1.1**), and the various criteria consequently employed in the literature, may contribute to these inconsistencies.

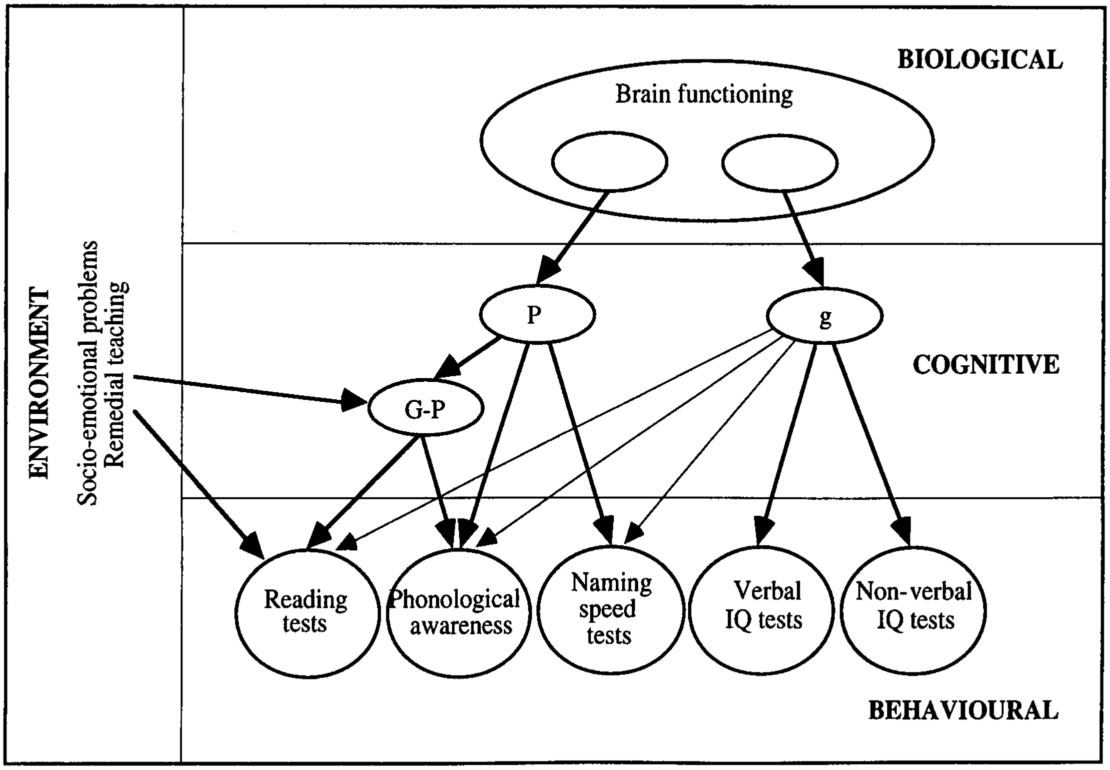
In view of the tremendous insights afforded into the psychophysiological substrate of reading by rapidly developing neuroanatomical imaging techniques it would be difficult to deny Pirozzolo and Hansch's (1982) observation that, "investigations examining the electroencephalogram under conditions of complex task involvement, particularly tasks involving various aspects of reading and other linguistic processes, represent a step forward in the assessment of neuroelectric correlates of brain dysfunction in children with reading disorders".

4.5. Summary and aims of the present thesis:

Behavioural and electrophysiological investigations of reading ability, and the specific cognitive processes associated with reading, have been discussed. These studies generally follow a number of assumptions: (1) that variations in literacy and in cognitive processing ability reflect naturally occurring variations in the neurological substrate, such that the abilities of the individual are relatively coherent and enduring; and (2) that a child's performance on any behavioural measure of cognitive processing ability will be influenced by numerous factors both internal to, and external of, the individual. It is further accepted that these specific cognitive processing skills are independent of general cognitive ability as measured by intelligence tests (Torgesen, 1986; Wagner, Torgesen, Laughon, Simmons & Rashotte, 1993). These assumptions have been incorporated into Frith's (1995) theoretical framework for representing the processing abilities of children at different points along the reading ability continuum. As illustrated in **figure 4.1** this framework encompasses three levels of explanation: biological, cognitive and behavioural. The influence of environmental factors is also recognised, although this influence is constant at all levels.

Frith's model is to provide the theoretical underpinnings of the work reported in the present thesis. This is to comprise 3 main investigations of the relationship between literary competence, cognitive processing ability and the neuropsychological substrate of the two. A further aim is to validate the employment of hand skill and hand preference measures as indices of cerebral lateralisation in children of different ages and abilities.

Figure 4.1 Factors involved in cognitive processing (after Frith, 1995)



Key: g = general intellectual abilities; P = phonological processing abilities; G-P = grapheme-phoneme knowledge

The first investigation, reported in **Chapter 6**, involves the longitudinal testing of a large sample of children on a battery of cognitive tests, and on measures of handedness, over a period of 2 years as they acquire elementary reading skills. The findings from this study are to be extended through the cross-sectional studies reported in **Chapters 7** and **8**, designed to investigate the aforementioned relationship in children with *established* reading skills and in developmental dyslexics. These latter studies invoke more direct measures of hemispheric lateralisation - a dichotic listening task and a phonological oddball task, respectively - each with contemporaneous recording of ERPs. The dichotic listening task was selected to provide a 'crude' behavioural index of *inter*-hemispheric lateralisation, while the electrophysiological measures were employed to yield more 'subtle', *intra*-hemispheric (as well as *inter*-hemispheric), indices of the cortical profiles underlying literary development. A more detailed rationale for the selection of the particular tests used in each study will be given in **Chapter 5**, along with a description of the test materials and an outline of the procedure involved in their administration.

~ CHAPTER 5 ~

Methodological considerations

5.1. Introduction:

As noted in the previous chapter (**Section 4.5**), the studies reported in **Chapters 6**, **7** and **8** of the present thesis embrace all three levels of Frith's (1995) framework detailing the factors involved in cognitive processing. The behavioural measures employed were selected to tap different aspects of the reading process at the most fundamental level, and also to reflect the children's more general cognitive abilities and biological characteristics represented in the first two levels of the model (as discussed in **Chapter 4**). The extent to which these behavioural measures were successful in reflecting brain functioning at the biological level was further investigated via the employment of more direct, electrophysiological, measures. Descriptions of the test materials employed in the following experiments are given below together with a rationale for their use and details of their administration. Subsequent references to these tests and their administration can then be understood via the description of the measures given in this chapter.

5.2. Psychometric measures:

The cognitive test battery detailed over the ensuing sections, measuring phonological memory capacity, visual abilities, phonological processing ability and reading skill, was employed in all of the studies reported in the present thesis (**Chapters 6**, **7** and **8**). Verbal short-term memory and word reading ability were assessed using the digit span task and the single word reading task from the British Ability Scales (Elliott, Murray & Pearson, 1983). Visual processing ability was determined by combining the results of the block design and the matching of letter-like forms tasks, again from the British Ability Scales (Elliott *et al*, 1983); these two were selected to assess, respectively, general visuo-spatial ability and a more "reading-related" visual ability. Principle components analysis of the measures from the Scales has revealed that these tests both emerged as loading on a "visual factor" (Elliott , 1983; Elliott & Tyler, 1987). A phonological discrimination task (Bradley & Bryant, 1983) provided an objective measure of each child's phonological awareness, while handedness was assessed in terms of hand skill (using the Annett (1970, 1985) pegboard) and hand preference (the Annett (1970, 1985) hand preference questionnaire). The measures used to provide a more direct indication of cerebral lateralisation in the two cross-sectional studies included a verbal dichotic listening task (Springer, 1986; Bryden, 1988; Hugdahl, 1991) and a phonological oddball task (after Bradley & Bryant, 1983). These particular tests, tapping different cognitive domains involved in the reading process, were selected and administered in all of the studies reported in the present thesis, thus ensuring consistency. All of the tests had empirically demonstrated validity and reliability for children of the ages tested (Elliott, 1983; Bradley & Bryant, 1985; Annett, 1985, 1991). Specific details of these tasks are given below.

5.2.1. Digit Recall task (Used in the studies reported in chapters 6, 7 and 8):

The auditory digit span task included in the test battery represents the most commonly used measure of verbal memory for children (Ellis & Hennelly, 1980; Snowling & Hulme, 1989; Gathercole *et al*, 1992; Hulme & Roodenrys, 1995). Reports linking phonological short-term memory with current reading ability (Jorm, 1983; Torgesen, 1985; Baddeley, 1986; Hulme, 1988) and with future reading ability (Mann & Liberman, 1984; Jorm *et al*, 1986) in children have demonstrated its validity as a measure of the formation and retrieval of mental representations of phonological information.

Prior to the administration of the test, all subjects were informed that the purpose of the task was to see how good they were at remembering numbers. They were told that they would be required to listen to numbers spoken by the experimenter and then to repeat the numbers in the same order that they had heard them. The sheet of paper on which the numbers were written (see **Appendix 1**) was kept out of sight of the child. The numbers were subsequently read in an even monotone at approximately half second intervals. The last digit was read with a slight drop in the voice to indicate to the child that the number was the last in the series; this was to prevent the child from responding before hearing all of the numbers. The child was then prompted to repeat the numbers as heard. No explicit time limit was imposed on the child's repetition of the numbers, but the children were encouraged to, and actually did in practice, repeat the numbers immediately.

This particular digit span test consists of sequences of numbers of gradually increasing length, such that the first number sequences consisted of 2 digits, the second of 3 digits and so on. Five number-sequences were presented at each length and thus constituted a 'block' of test items. As this test is designed for children between the ages of 2 1/2 and 17 1/2 years, it was necessary to establish the "basal level" (Elliott *et al*, 1983) of each child individually from the outset. This was accomplished by presenting each child with the first number sequence from the first block of items (2 digits) for them to repeat. If this sequence was repeated correctly, the experimenter moved on to the first sequence in the next block (3 digits), and continued in this way until a sequence was either reported incorrectly or was not attempted. At this stage the experimenter moved back to the preceding block of numbers and administered the remaining sequences; once again, if any of these sequences were repeated unsuccessfully the experimenter moved back to the previous block. Testing continued in this manner until all five sequences of numbers in a single block had been failed (Elliott *et al,* 1983). Span was calculated as the maximum list length (i.e. block) at which the child correctly reported all of the digits.

5.2.2. Matching of Letter-like Forms task (See chapters 6, 7 and 8):

This task provides a measure of visual discrimination ability. Gibson (1969) reported that prior to the onset of reading instruction children often perceive reversed or rotated figures as constant. It is only as a result of exposure to written letters (and numbers) that children learn that the orientation of a figure is crucial for its identification. Thus, the visual discrimination ability assessed by this task appears to be important to the acquisition of literacy skills. It is hardly surprising that longitudinal and cross-sectional studies have revealed differential visual discrimination abilities in children of varying literacy skills and ages (Adelman & Taylor, 1986; Spreen & Haaf, 1986; Feagans & Merriwether, 1990).

Subjects were informed that the matching of letter-like forms task was designed to see how good they were at matching different shapes and patterns. The test booklet was opened and the child's attention drawn to the single figure at the top of the page (see **Appendix 2**). Subjects were then asked to point to the figure on the lower page which exactly matched the target shape. Any incorrect responses to the first three stimuli were scored as failures but subjects were given corrective feedback if necessary (this was rarely required). Incorrect responses to subsequent stimuli were scored as failures but were not corrected by the experimenter to prevent discouraging the child. Testing continued progressively through the booklet, at the child's own pace, until all 16 letter-like forms had been attempted.

5.2.3. Block Design task (Used in the studies reported in chapters 6, 7 and 8):

Block design tasks have been employed with children of different ages and reading abilities to provide an indication of visual skills that are relatively independent of memory, language or vocabulary (Ellis & Large, 1987; Siegel, 1989; Valdois *et al*, 1995).

As instructed in the administration manual (Elliott *et al*, 1983), this task was prefaced by giving the child the blocks to examine while the experimenter drew the child's attention to the colours on the sides of the blocks. Having established that all the blocks were identical the experimenter informed the child that the purpose of the task was to arrange the blocks into patterns, so that the designs on the top of the blocks matched those printed in the test booklet (see **Appendix 3**). The first pattern was reproduced by the experimenter for the child to copy.

The child subsequently worked through each of the patterns in the booklet within the time limits specified in the administration manual. The time allowed for each design (as instructed in the manual) was indicative of the difficulty of the pattern. A maximum of 45 seconds for the first five designs, 90 seconds for the next six designs and 120 seconds for the last five designs. If the child failed to produce any pattern within the time allowed, the trial was deemed unsuccessful. The task continued until the child had either completed all of the designs or had failed on four consecutive items, as specified in the discontinuation instructions in the test manual.

5.2.4. Phonological Oddity task (Administered in all studies - see chapters 6, 7 and 8):

Phonological awareness was determined through the administration of Bradley & Bryant's (1983) phonological discrimination task. This task was selected in preference to the numerous other measures of phonological awareness which are available (tests of phonemic segmentation, addition or deletion, for example), as performance of these measures is reported to depend on pre-existing orthographic knowledge (Ehri & Wilce, 1980; Mann, 1986; Read *et al*, 1986). The phonological oddity task, however, may be performed by pre-literate children as young as 3 years old (Maclean *et al*, 1987), and has been shown to provide a valid indication of the child's subsequent literacy skills (Bradley & Bryant, 1983; Bryant *et al*, 1990).

Prior to the administration of the phonological discrimination task the child was told that the task involved words which sounded the same. The precise instructions given differed as to whether the child was in the longitudinal study or one of the cross-sectional studies. To introduce the notion of rhymes, the younger children in the longitudinal study were prompted to recite a nursery rhyme; this was subsequently repeated by the experimenter who emphasised the rhyming words. These children were then encouraged to produce further words to rhyme with words given by the experimenter. The children in the cross-sectional studies, being older, were simply asked to produce rhyming words in response to words spoken by the experimenter. The words chosen in each instance were selected at random from the rhyming conditions of the phonological discrimination task. The alliteration condition of the task was similarly introduced to both groups of children by the experimenter providing words which started with the same letter (words such as "ball, bed, balloon") and the child was encouraged to produce further words starting with the same sound.

The precise nature of the task was then explained. The child was told that four words would be spoken, of which three would sound similar and one would sound slightly different. The child was asked to indicate the "odd-word-out" after hearing each set of words. A couple of practice trials introduced each condition (first-, middle- or last-sound-different; see **Appendix 4** for the test words) and corrective feedback was provided if necessary. The experimenter subsequently worked through the task reading each word with equal emphasis at approximately 2 second intervals. If a child failed to answer and requested that the word be repeated this was granted, as indicated in the test manual (Bradley, 1980); no repetition was made if the child had already guessed at the odd word. The task continued until all the test trials had been attempted.

5.2.5. Word Reading task (See chapters 6, 7 and 8):

The single word reading test was chosen in preference to measures involving the reading of textual passages, or reading comprehension tests, as these latter types of reading test would have been impossible for many of the children tested in the present studies. In the pursuance of consistency a test was required which could be used across all studies and at all stages of the longitudinal testing. In interpreting the results of this test it must be remembered that the score obtained by a child is purely a measure of its sight vocabulary, without the aid of contextual clues. Thus, a child obtaining a score of two on such a test could not only read two words, but it could only read two of the words presented in this particular test (see Bowey, 1994 for a discussion). It may be argued that single word reading tasks do not measure "real" reading ability. On the contrary, however, the reading of individual words is of primary importance in the development of literacy (Marsh *et al*, 1981; Seymour & MacGregor, 1984; Frith, 1985). It is necessary, although not sufficient, for fluent reading (Coltheart & Rastle, 1994), and it is the source of difficulty in dyslexia (Vellutino, 1978; Pennington *et al*, 1991). Furthermore, scores obtained on single word reading tests are reported to correlate highly with those obtained from measures of comprehension, speed and accuracy of reading prose passages (Elliott, 1983). In view of the fact that reading comprehension tests depend on an interaction of a number of different factors, including reading speed, vocabulary, memory and prior knowledge, it has been suggested that single word reading tests are, in fact, the purer measures of a child's reading ability (Siegel, 1985; Siegel & Heaven, 1986).

Word reading ability was assessed, therefore, by presenting subjects with a list of individual words to be read aloud. These words constituted the word reading test of the British Ability Scales (Elliott *et al*, 1983; see **Appendix 5**). As directed in the manual, this test continued until the child had either read all of the words correctly (a possible maximum of 20 words) or had failed on five successive words. No corrective feedback was given by the experimenter.

5.3 Measures of cerebral lateralisation:

Hand preference and hand skill measures were used in the studies reported in **Chapters 6, 7** and **8** to provide indirect indices of cerebral lateralisation. The dichotic listening task was used in addition to these measures, to provide a more direct index of cerebral lateralisation, in the cross-sectional studies reported in **Chapter 7**. The phonological oddball task was employed for this purpose in the study reported in **Chapter 8**.

5.3.1. Handedness measures:

Two measures were employed to accommodate Provins, Milner & Kerr's (1982) argument that to classify an individual's handedness solely on the basis of a single measure is to grossly over-simplify the case. Evidence suggests that measures of hand skill and preference (as determined by paper & pencil questionnaires) are often poorly correlated, as hand preference often does not depend upon differences in skill (Peters & Pang, 1992; Bryden, Singh, Steenhuis & Clarkson, 1994). The present studies aimed to circumvent this problem by combining the findings from related measures of hand skill and preference, both of which have demonstrated construct validity (see Annett, 1992a).

5.3.1 (a) Pegboard task (hand skill):

Hand skill was determined using the Annett (1970) pegboard task. This measure has been widely used as an indirect assessment of laterality with individuals of all ages (from 4 years through to adulthood; see Annett, 1985) and in children of varying intellectual abilities (Annett & Manning, 1989, 1990a, b).

To complete this task the children were stood, one at a time, in front of a table on which a pegboard was rested. They were instructed that on the word "go" (of "ready, steady, go") their task was to move a row of 10 doweling pegs from a further row of holes to a nearer row one peg at a time, using only one hand (see **Appendix 6** for the testing set-up); the hand used to perform the task alternated between trials. The children worked from right to left when the right hand was used and from left to right when the left hand was used; this procedure was demonstrated. Each trial commenced with the child's hand placed on the first peg and the time taken to complete the task was measured using a stopwatch, from the word "go" until the final peg had been released. If the child dropped a peg the trial was stopped and re-started from the beginning. Following a successfully completed trial, the board was turned around in preparation for the next trial. The hand used to perform the first trial was alternated between children.

This procedure continued until each child had successfully completed the task, three times with each hand by the children in the longitudinal study, five times by the children in the cross-sectional study. The younger children performed the task only three times per hand to prevent them from losing interest in the task while still enabling the calculation of a mean performance score (see Annett, 1970, 1985).

5.3.1 (b) Annett Handedness Questionnaire (hand preference):

Hand preference was assessed by administering the Annett Handedness Questionnaire (A.H.Q.,1970, 1985; see **Appendix 7**). This is an objective measure of hand use selected in preference to the other commonly used measure of hand preference, the Edinburgh Handedness Inventory (E.H.I.: Oldfield, 1971). This selection was made on the basis of a number of practical considerations. Firstly, unlike the E.H.I., the A.H.Q. makes no demands on the children to judge the strength of their hand preferences (i.e. to rate the hypothetical possibility of using the non-preferred hand), it merely requires a demonstration of which hand is normally used to perform a particular task. Secondly, the fundamental tenet of the E.H.I., that all of the actions are of equal importance in the assessment of an individual's laterality, appears rather naive, in that the summation of all responses conceals underlying lateral preferences. The A.H.Q. overcomes this problem by weighting the actions according to their significance; i.e. the hand used for performing "primary" actions - writing, throwing a ball at a target or for holding a toothbrush, for example - is given greater consideration in the calculation of the overall preference score than the hand used to perform "secondary" actions - such as holding a broom or a spade (see Annett, 1992). In the present study the objects referred to in the A.H.Q. were provided for the children to use, thus enabling a far more empirically valid measure of hand preference than that yielded by subjective paper and pencil measures (Annett, 1992a; Bryden *et al*, 1994). The experimenter made a note of which hand was used in each instance.

5.3.2. Dichotic listening task:

The verbal dichotic listening technique provides a behavioural index of the relative participation of the left and right cerebral hemispheres in the perception and processing of language. It is, therefore, a fairly direct measure of cerebral lateralisation. Stimuli presented to the right ear, for example, tend to be reported with greater accuracy than stimuli presented simultaneously to the left ear (Mondor & Bryden, 1991; Ahonniska *et al*, 1992; Duvelleroy-Hommet *et al*, 1995). This simple, non-invasive task, which has theoretical and empirical validity, is considered to provide the most accurate indication of hemispheric functional lateralisation of any of the behavioural techniques employed with non-clinical subjects (Harper & Kraft, 1986; Annett, 1991; Boliek & Obrzut, 1995).

Prior to the administration of this task subjects were told that they would be given a pair of headphones to wear, through which they would hear a man's voice saying different "nonsense words". These stimuli were printed on a piece of card which was shown to the child (see **Appendix 8**) while the experimenter read the words aloud. The child was informed that two of these words would be heard, one in each ear simultaneously, and that having heard them the child would be required to report those heard in the ear (or ears) previously identified by the experimenter. Guessing was encouraged. A brief practice session followed to enable the subjects to become familiar with the sound of the dichotic stimuli and to ensure that they were certain as to what was required of them. No subject actually experienced any difficulty in understanding the requirements of the task.

Three response conditions were employed: (1) free recall, in which the child was required to verbally report the syllables heard in both ears, although the order of report was optional (left ear then right ear, or right ear then left); (2) forced right ear recall, in which the child would still hear sounds through both ears, but they were only to report stimuli presented to the right ear; and (3) forced left ear recall, in which the subject was told to report only stimuli presented to the left ear. These conditions were presented in a random order between subjects. Within each condition 32 consonant-vowel (C-V) syllable pairs (/ba/, /da/, /ga/, /ta/, /pa/, /ka/) were presented. Each C-V pair was presented for 320 milliseconds, with a 4 second inter-stimulus interval. The stimuli, read by a digitised adult male voice with the same intonation on each syllable, were recorded onto cassette tape (tape EDLCV- 96). This tape was adapted from material supplied by the Department of Biological and Medical Psychology, University of Bergen, Norway (see Hugdahl & Andersson, 1987). Stimuli were presented at 75 dB using a BASF 8200 Hi-fi Stereo Deck with EH 310 stereo headphones. Although it would have been desirable to reverse the headphones half way through the task to compensate for any inequalities in signal-to-noise ratio between the channels, this would have introduced a confounding variable into the scoring of the directed attention conditions (in which it is necessary to know which CV syllable was heard in which ear) so was avoided. Any possible inequalities in the signals relayed through each ear of the headphones were eliminated by careful calibration of the two channels.

5.3.3. Phonological oddball test:

Cerebral lateralisation for the processing of phonological information was assessed by using a phonological oddball task. Bradley and Bryant's (1983) phonological oddity task elicits different performances from good and poor readers (Bradley & Bryant, 1985; Maclean *et al*, 1987; Brunswick & Rippon, 1994). A modification of this task was employed in the cross-sectional study reported in **Chapter 7**. Three blocks of words were presented, within each of which were two "libraries" of words, the frequent words and the rare (oddball) words. The frequent words within each block shared either their first, middle or last sounds as illustrated below; the rare words within each block differed from the frequent words primarily on the basis of this shared (first, middle or last) sound.

<u>First-sound-different condition</u>:

Frequent words:	bat	back	ban	bad	bag	ban	bam	bap
Rare words :	tap	mat	fan	sack	rag	ham	mad	cat

<u>Middle-sound-different condition</u>:

Frequent words:	red	fed	bed	dead	led	head	said	wed
Rare words :	fad	bud	lid	had	mud	cod	sad	did

<u>Last-sound-different condition</u>:

Frequent words:	cat	hat	mat	bat	sat	fat	pat	rat
Rare words :	fan	sad	rag	pan	mad	cap	ham	bag

The rare words were similar in length to the frequent words: between 356.38 and 776.02 milliseconds in duration (see **Appendix 9** for individual times). The stimulus words, read by a female voice with the same intonation on each word, were recorded onto an Apple Macintosh IIci microcomputer which presented the words in a pseudo-random order via stereo loud speakers. Words were presented with a 2.5 second inter-stimulus interval and a frequency of 500 Hz. The probability of presentation of a rare word was set at 25%, and presentations continued until 16 rare words had been heard; this number was selected to provide a reliable indication of the child's phonological processing abilities without rendering the task unduly tedious. After each presentation the experimenter recorded both the word presented and the subject's response.

Before the presentation of each block of words the children were told which condition was to be presented. They were informed that their task was to listen to the words - to either their first, their middle or their last sounds - and to respond to each word by saying "same" if the word shared the characteristic sound, or "different" if it did not. Examples of the words in each condition were provided and practice trials, with corrective feedback where necessary, were given for each block of words until the experimenter was satisfied that the child understood what was required; no child experienced any difficulty in understanding the requirements of the task. The importance of attempting to respond to every word was stressed, and guessing was encouraged in cases of uncertainty.

5.4 Electroencephalographic measures:

Electroencephalographic measures were taken during the performance of the dichotic listening and phonological oddball tasks in the cross-sectional studies reported in **Chapters 7** and **8**. Event-related potentials (ERPs) recorded from over the left hemisphere have been reported to be of larger amplitude than those recorded from over the right hemisphere during the processing of linguistic information (Papanicolaou *et al*, 1983; Van de Vijver *et al*, 1984; Brunswick & Rippon, 1994). This may reflect the localisation of linguistic processing within the left hemisphere. Within the ERP waveform three components are of particular interest to the present studies: the N100, the P200 and the P300. The earlier components - the N100 and P200 - are thought to reflect sensory and attentional factors (Vaughan *et al*, 1983; Naatanen & Picton, 1987), while the P300 is manifested during cognitive processing (Donchin *et al*, 1986; Donchin & Coles, 1988). ERPs were recorded in each of the cross-sectional studies, during the performance of the dichotic listening (focusing on the N100 and P200 components) and the phonological oddball (P300) tasks.

5.4 .1. Fitting the electrode cap:

Prior to the start of the testing, each child was fitted with a commercially available electrode cap (Electro-cap International, Inc.). Incorporated into the cap were 28 tin electrodes arranged according to an implemented 10/20 electrode placement system (Jasper, 1958 - see **Appendix 10**) to ensure consistency of placement. This elasticated cap was secured to the child's head by means of elastic straps clipped onto a chest band (see **Appendix 11**). Each of the 28 scalp electrodes and 2 ear electrodes was subsequently filled with conducting electrode gel (Electro-Gel: Electro-cap International, Inc.), during which time the child sat watching a video of "Tom and Jerry" cartoons to keep them occupied but relaxed.

5.4 .2. ERP recording:

A NeuroScience Brain Imager (Series III) was used to record ERP data from the scalp and linked ear reference electrodes (see **Appendix 12**). Impedances of all electrodes were below 5.6 kΩ. Recordings were made with a bandpass of 0.30- 40 Hz, digitised at 500 Hz for 1000 msec post-stimulus. Waveforms were averaged on-line.

During the testing sessions the children were instructed to keep their heads and bodies still and their eyes closed to avoid artefact produced by extraneous muscle movement.

Following the completion of testing the individual measures were scored, as detailed below, in preparation for statistical analysis.

5.5. Data Reduction:

5.5.1. Psychometric measures:

Each of the psychometric measures from the British Ability Scales was marked in accordance with the scoring instructions provided (Elliott *et al*, 1983). Bradley & Bryant's (1983) phonological discrimination task was scored to provide individual measures of accuracy for the "first-sound-different", "middle-sound-different" and "last-sound-different" conditions (each out of a maximum of 8).

5.5.2. Handedness measures:

Mean scores for the completion of the pegboard task by each child's left and right hands were calculated and applied to the equation:

$$\frac{(\text{Left hand time} - \text{Right hand time})}{(\text{Left hand time} + \text{Right hand time})} * 100$$

to provide an index of hand skill (see Annett, 1970). Negative scores represent faster left hand times; positive scores indicate an overall right hand advantage. This relative measure enables comparisons of left and right hand skill to be made between children of different ages without the confounding effects of age-related changes in overall performance.

An indication of hand usage was obtained by scoring the hand preference questionnaire as in Annett (1970, 1985), with a hand preference score of 1 representing "pure right" handedness and a score of 8 indicating "pure left" handedness.

5.5.3. Dichotic listening task:

The dichotic listening task was scored as in Hugdahl and Andersson (1987) to provide number of correct responses for both the left and right ears during the free recall condition and number of correct responses for the left and right ears respectively in the forced left and forced right conditions. These scores were applied to the equation:

$$\frac{(\text{Left ear correct} - \text{Right ear correct})}{(\text{Left ear correct} + \text{Right ear correct})} * 100$$

(see Harshman & Lundy, 1988). This procedure yields ear advantage indices for each recall condition while adjusting overall accuracy in each ear in relation to total accuracy.

5.5.4. Phonological oddball task:

The P300 phonological oddball task was quantified by totalling the number of correct "rare" and "frequent" responses within each of the stimulus conditions. As the stimuli were presented randomly by a computer (the probability of presentation of a "rare" stimulus in each instance was 25%) the number of stimuli in each condition varied between subjects. To enable between- and within-subject comparisons to be made percentage scores were calculated for each subject in each of the recall conditions by applying the scores to the equation:

$$\frac{\text{Total number of correct responses}}{\text{Total number of possible responses}} * 100$$

5.5.5. Electroencephalographic measures:

Although ERPs were recorded from all 28 scalp electrodes, only data from a sub-set of these electrodes were analysed. These electrodes included those covering the midline (Fz, Cz and Pz), the frontal (F3, F4), central (C3, C4), parietal (P3, P4) and temporal (T5, T6) brain regions (see **Appendix 10**). The midline electrodes were selected as evoked potentials are maximally recorded at the vertex (Cooper *et al*, 1980; Picton, 1992). The data from the lateralised sites are taken to be representative of the activation in each of the cortical lobes (and in each hemisphere) during the processing of the stimuli, thus providing an indication of relative hemispheric specialisation for the perception and processing of verbal information (Johnson, 1993).

Prior to analysis of the ERP waveforms the averaged evoked potentials were visually inspected for artefact and records containing eye movement or overt muscular artefact were precluded from statistical analysis. In quantifying the ERP data peak amplitude was taken in each case as the voltage difference (in μV) between the identified peak and the (20 msecs) pre-stimulus baseline level; latency was recorded as the interval (in milliseconds) between stimulus onset and the occurrence of the designated peak (Coles *et al*, 1990; Picton, 1992).

These values were subsequently entered into an Apple Macintosh Systat package in preparation for statistical analysis. Significance levels for all analyses were adjusted with the Greenhouse-Geisser procedure (Greenhouse & Geisser, 1959); Tukey's Honestly Significant Differences (HSD) test was used as a post-hoc investigation of significant results. To circumvent the potential statistical dangers inherent in the performance of multiple Tukey tests within a single series of pairwise contrasts (an increased risk of committing a Type 1 error), results were not considered significant unless the probabilities proved less than 0.05 divided by the number of contrasts (i.e. 2 pairwise contrasts would demand the adoption of a significance level of 0.025).

Precise details of the analyses involved in the longitudinal and cross-sectional studies are provided in **Chapters 6**, **7** and **8**.

~ CHAPTER 6 ~

Cognitive and behavioural correlates of reading acquisition: A longitudinal study

6.1 Introduction:

Longitudinal studies have provided valuable insights into the relationship between cognitive ability and reading development in the young child (Perfetti *et al*, 1987). For example, Torgesen, Wagner & Rashotte (1994) charted the relationship between emerging reading skills and 22 measures of phonological awareness and general verbal ability in children at the start of each school year from kindergarten through to second grade. The results of this study will be presented below (sections **6.1.1** and **6.1.2**). Such studies have generally focused on those specific cognitive abilities which are thought to exert a causal influence on reading development. As exemplified by Torgesen *et al*'s (1994) study, longitudinal investigations have generally focused on abilities such as phonological awareness (Wagner & Torgesen, 1987; Torgesen *et al*, 1994), phonological short-term memory (Mann & Liberman, 1984; Jorm *et al*, 1986; Ford & Silber, 1994), or visual processing skills (Bond & Dykstra, 1967); these studies are reviewed over the ensuing sections. Relationships between the development of reading ability and the development of these cognitive abilities can then be observed.

6.1.1 Phonological awareness and reading development

Phonological awareness appears to be of particular importance in learning to read (Perfetti *et al*, 1987; Goswami & Bryant, 1991). Children who demonstrate good phonological skills in kindergarten, prior to the commencement of formal reading instruction, are typically found to acquire early literacy skills far more easily than children with poor phonological ability (Bradley & Bryant, 1985; Felton & Wood, 1989;

Byrne *et al*, 1992). In fact, not only does kindergarten phonological awareness correlate significantly with reading ability at the end of the first year of formal schooling (Lundberg *et al*, 1980; Mann & Liberman, 1984; Torgesen *et al*, 1994), but phonological processing ability in the 3-4 year old pre-literate is also found to be predictive of reading ability in the 7-8 year old child (Wagner & Torgesen, 1987; MacLean *et al*, 1987 - see chapter **2**). While it has been suggested that this relationship is causal (Bradley & Bryant, 1983, 1985), the precise direction of this causality remains to be empirically determined.

6.1.2 Phonological memory and reading development

As noted in **Chapter 2**, phonological awareness may also mediate reading development via its influence over phonological memory (Wagner & Torgesen, 1987; Crain *et al*, 1990; Gathercole & Baddeley, 1993). The phonological storage of information is important in the novice reader, both for the identification of individual words during the application of grapheme-phoneme correspondence rules and to facilitate the comprehension of text (Daneman & Carpenter, 1980; Baddeley, 1986).

It is of little surprise, therefore, that longitudinal correlation studies have found memory span in kindergarten to be predictive of reading ability at the end of year one (Mann & Liberman, 1984; Jorm *et al*, 1986; Torgesen *et al*, 1994), or that cross-sectional studies of good and poor readers have reported phonological memory deficits in the latter group of children (Siegel & Linder, 1984; Hulme, 1988; Rapala & Brady, 1990). Such findings have supported the suggestion that the acquisition of fluent reading skills is dependent upon an interaction of verbal processing and temporary storage requirements (Daneman & Tardif, 1987). What is surprising, however, is that in spite of the evidence linking phonological memory and reading via phonological awareness, there remains a relative dearth of evidence concerning the precise relationship between these abilities in children over the early stages of reading development.

6.1.3 Visual processing skills in relation to reading development

In the first stages of reading, before the application of grapheme-phoneme correspondence rules to decode unfamiliar words, it is argued that children identify words predominantly on the basis of their overall shape (i.e. during Marsh *et al*'s (1981) "linguistic substitution" phase or Frith's (1985) "logographic" stage of reading acquisition: see **Section 2.2**). One early study reported moderate correlations (between 0.3 and 0.5) between visual processing skills (the ability to copy graphic patterns and to discriminate between simple forms) in the pre-literate child and its reading ability at the end of the first year at school (Bond & Dykstra, 1967). The proposition that this early dependence on visual processing facilitated reading led to an examination of the differential effect of good and poor visual skills on reading development (Bond & Dykstra, 1967; Chall, 1978). Until fairly recently, visual perceptual deficits were considered to be the major cause of reading problems in dyslexic children (Frostig & Horne, 1964; Blachman, 1983: see also **Section 3.4**). Over the last decade, however, a growing awareness of the predominant role played by language-based skills in reading acquisition has reduced the level of interest in the influence of visual-perceptual abilities. Although perhaps not as important as language-based skills, perceptual factors are still important. Studies of the cognitive deficits underlying dyslexia suggest that to dismiss the influence of visual perceptual factors on reading development may be rather unwise (Stein, 1991; Dautrich, 1993; Cornelissen *et al*, 1991, 1994).

6.1.4 Neuropsychological correlates of cognitive processing

Evidence from neuropsychology indicates a complex relationship between cognitive processing abilities and cerebral lateralisation. This relationship is such that any deviation from the expected pattern of predominantly left hemisphere mediation of verbal, right hemisphere mediation of non-verbal, processing in dextrals (i.e. a reduction in the left hemisphere's superiority for the processing of language) would have obvious implications for a child's reading development. Difficulties with phonological processing, for example, have been observed in conjunction with a failure to exhibit the expected pattern of larger left than right hemisphere brain regions; this is taken to reflect abnormal development of the left hemisphere's auditory system (Larsen *et al*, 1990; Wood *et al*, 1991; Galaburda *et al*, 1994- see **Chapter 4**). Conversely, difficulties with visual aspects of reading have been found in association with an over-reliance on left hemisphere processing, as indexed by electrophysiological and handedness measures, suggesting some form of abnormal development of the right hemisphere (Bakker, 1980; Annett & Manning, 1989; Rippon, 1991).

This relationship between cognitive ability and cerebral lateralisation has also been observed by taking measures of handedness (hand skill and preference) as indirect indices of lateralisation (Annett & Manning, 1990b; Annett, 1992a; Brunswick & Rippon, 1993, 1994; see **Chapter 4**). The repeated measurement of handedness in children during the period of early reading acquisition has yet to be undertaken, however.

6.1.5 Longitudinal studies of reading development: A critique

The preceding overview of the literature shows that substantial information is known about the relationships between reading and the numerous cognitive factors which support its development. Unfortunately, there still remain critical gaps in this knowledge; these are due largely to methodological flaws in the studies concerned.

One such flaw is the tendency of some studies to consider a single cognitive factor thought to be involved in the reading process and to focus on it to the exclusion of other possible causes of individual differences in reading development (e.g. Wimmer *et al*, 1991; Stahl & Murray, 1994; Siegel, 1994). While this approach provides some indication of the one-to-one relationship between the specific cognitive ability under investigation and reading development, it fails to take account of the child's cognitive development as a whole. Learning to read is a complex task involving numerous cognitive skills, many of which may be inter-related (Ellis & Large, 1987). By focusing exclusively on any one of these skills researchers are rendering themselves liable to become so engrossed in the individual 'trees' as to fail to notice the 'wood' for which they are exploring. As Ellis & Large (1987) point out, "...unless all of (the) determining factors are taken into account... the resultant whole is a patchwork of views... a gross generalisation (which) does not allow easy comparison of important effects. Only differential studies of the same children allow this " (p. 2).

The latter part of Ellis & Large's caution also highlights another problem with this research. Many researchers intent on investigating the relationship between cognitive factors and reading ability at different stages of reading development eschew the longitudinal study in favour of the cross-sectional study (Leather & Henry, 1994; Siegel, 1994; Stahl & Murray, 1994). Whereas the former involves the repeated testing of an established sample over time the latter involves a comparison of subjects of different ages or abilities. The only valid way in which to study the developmental changes associated with reading is to test the same group of subjects repeatedly over time. In view of differences in teachers and in teaching methods, and to avoid making the sweeping assumption that the abilities of a younger sample are identical to those of an older sample at some previous point in time, cross-sectional studies, comparing different groups of children at different stages of development, must always be considered inferior to longitudinal studies (Ellis & Large, 1987).

A problem commonly observed in longitudinal studies of reading development is the measurement of a particular cognitive skill at an initial stage of testing (usually in kindergarten) with attempts to relate this measure to reading ability assessed at a later stage (generally some time in the first year of formal schooling). Such designs (e.g. Mann & Liberman, 1984; Mann, 1984) fail to take into account possible causal influences of extant reading skills at stage one over reading ability at stage two, thus leading researchers to potentially overstate the influence of the cognitive variable under investigation. This methodological problem is overcome by assessing reading skills at every stage of testing over a longitudinal period, even if only to objectively determine that the children initially possess no literacy skills. This is the design adopted in the present study.

A related trap into which many reading researchers fall is the failure to consider the possibility of reciprocal causality between each of the cognitive measures and reading ability (e.g. Mann & Liberman, 1984; Stanovich *et al*, 1984; Bradley & Bryant, 1985). Evidence suggests, for example, that in addition to the influence which phonological awareness has on reading development, the acquisition of reading skills also enhances phonological awareness (Morais *et al*, 1987; Perfetti *et al*, 1987). To examine the emerging relationship between reading and other cognitive abilities on which it depends it is necessary to measure all of the variables of interest at every stage of testing. This procedure, undertaken in the present study, enables a comprehensive investigation of the development of reading within its cognitive context.

There is also the danger of undertaking too few testing sessions, too infrequently. Many self-professed longitudinal studies, for example, consist of two testing sessions, separated by a year; these are usually at the end of kindergarten/ start of grade one and again at the end of grade one (Juel *et al*, 1986; Gathercole & Baddeley, 1989; Wimmer *et al*, 1991). Evidence suggests that the progress made by children over the first year of reading instruction is rapid (Oakhill & Garnham, 1988; Adams, 1990). Such infrequency of testing, therefore, will prevent researchers from observing in any great detail the emergence of children's reading skills in relation to the development of pre-existing cognitive abilities. Furthermore, ending the longitudinal testing after a single year will obviously limit the potential wealth of information to be obtained from the study (Wagner & Torgesen, 1987). Studies involving the testing of children in two sessions, one year apart, may be an insensitive measure of the development of particular cognitive/ reading skills.

A further problem with some longitudinal studies is the testing of small cohorts of children; typically in the region of 20 (Treiman & Baron, 1983; Seymour & Elder, 1986), 40 (Cunningham, 1990; Catts, 1991) or 50 (Juel *et al*, 1986; Wimmer *et al*, 1991). Many such studies employ a large battery of cognitive tests, usually somewhere between 5 and 10 (Bryant *et al*, 1990; Cunningham, 1990) but also up to 15 (Juel *et al*, 1986) or 22 tests (Torgesen *et al*, 1994). Data derived from longitudinal studies are typically analysed using a within-subjects analysis of variance (ANOVA) with repeated measures. Such a design is problematic, however, in that it is prone to a high degree of inter-correlation amongst the means on which comparisons are based, thus increasing the risk of eliciting a Type 1 error. One means by which this risk may be reduced (i.e. the power of the test increased) is by testing large numbers of subjects - a minimum of $n = k + 20$, where k = the number of conditions - the larger the number of subjects the greater the statistical power.

6.1.6 The rationale underlying the present study

The present study was designed to observe the relationship between individual reading skill and intellectual development in children from 3 and a half to 5 and a half years old. In the light of the above criticisms a longitudinal study was undertaken. This employed a battery of cognitive measures administered to a sample of 142 children every 6 months over a 2 year period of early reading development. This study conformed to Wagner & Torgesen's (1987) recommendations that longitudinal studies should ideally comprise a large group of children tested on at least three occasions, initially before the children could read (this should be tested objectively), secondly at a stage of early reading acquisition and subsequently at regular stages of reading development.

The primary aim of the following study was to investigate the relationship between reading skills and fundamental cognitive abilities in a large sample of children as they enter the early stages of reading acquisition. A further aim was to attempt to chart the biological basis of reading development through the assessment of the children's handedness as an indirect measure of cerebral lateralisation. These relationships were broached from a predictive point of view to determine the possibility of ultimately predicting a child's reading ability at the age of 5-6 years from their cognitive abilities at the age of 3 1/2.

6.2 Method:

The longitudinal study was undertaken in five stages. As there was some movement in subject numbers from stage to stage, the number of children tested at each stage varied. Discrepancies, however, were not large. Details of these samples are noted below.

6.2.1 Subjects:

6.2.1 (a) Testing session 1:

At the first testing stage 142 children, attending two nursery schools in Nuneaton, participated. Permission for testing the children was sought and obtained from parents. Although it was not possible to classify the children according to socio-economic status the two schools were selected - one in a suburban area of the town, the other on a council estate - so as to provide a representative cross-sectional sample of the population.

This initial sample was tested in the December of the children's first year at nursery school, after 3 months of schooling. It comprised 72 girls and 70 boys. Ages ranged between 3:02 and 4:05 years (mean age = 3:46 years ± 0.46). Of these children 118 (59 boys and 59 girls) were overtly dextral, in that they chose to hold a pencil in their right hands for drawing a circle; 24 (11 boys and 13 girls) were sinistral, in that they held the pencil in their left hands. More extensive measures of hand preference are reported in **Section 6.5.2**.

6.2.1 (b) Testing session 2:

The second testing session occurred in June at the end of the nursery school year, and 6 months after stage 1. One of the girls had moved away from the area, while another boy had joined the nursery and was included in the sample. Thus, the overall number remained stable at 142 children (71 girls and 71 boys). This sample ranged in age between 3:07 and 4:10 years, with a mean age of 3:90 years (± 0.34). Once again, 118 of these children (61 boys and 57 girls) were right hand preferent for drawing and 24 (10 boys and 14 girls) were left hand preferent.

6.2.1 (c) Testing session 3:

At the third session, 6 months after stage 2, the children had moved (3 months previously) from the nurseries to begin full time education at junior school. While the majority of the children moved to the schools to which the nurseries are attached, a minority moved to various schools in other parts of Nuneaton. These children were not tested further due to the practical difficulties of gaining access to them at six month intervals. The experimental sample by this stage consisted of 56 boys and 52 girls (N= 108), aged between 4:02 and 5:05 years (mean age = 4:46 years ± 0.46). Assessment of hand preference for writing revealed that 93 of the children (49 boys and 44 girls) were dextral and 15 (7 boys and 8 girls) were sinistral.

6.2.1 (d) Testing session 4:

Stage 4 occurred at the end of year one of formal schooling (another 6 months after stage 3). The fourth sample comprised 56 boys and 51 girls (N= 107) with a mean age of 4:91 years (± 0.34) and a range from 4:07 to 5:10 years. Ninety of these children (48 boys and 42 girls) held a pencil in their right hand for writing their names whereas 17 children (8 boys and 9 girls) wrote with the pencil in their left hands.

6.2.1 (e) Testing session 5:

The final sample was seen in the December of year 2 at school, again, 6 months from the preceding stage, and consisted of 104 children (53 boys and 51 girls). One boy moved away from the area prior to the final stage of this session, so hand preference and reading ability data are not available for this subject. The children's ages at this stage ranged between 5:04 and 6:03 years (mean = 5:36 years ± 0.43). Hand preference measures revealed that of the 103 children in this sample for whom a complete data set was available 87 (42 girls and 45 boys) were dextral for writing and for the majority of the uni-manual actions tested (and outlined in chapter 4), whereas 16 (9 girls and 7 boys) showed sinistral preferences for the performance of these actions.

6.2.2 Stimuli and Apparatus:

6.2.2 (a) Indirect measures of cerebral lateralisation (hand preference and skill):

The children's left and right hand skill was determined through the use of the Annett (1970) pegboard task. This task was administered according to the procedure outlined in **Chapter 5**. Each child's hand preference for the performance of various uni-manual activities was determined using the Annett (1970) hand preference questionnaire (described in **Chapter 5**).

6.2.2 (b) Neuropsychological measures:

A battery of tests was administered to the children to assess their cognitive processing abilities. Their auditory short term memory, visual matching, visuo-spatial and reading skills were quantified using the recall of digits task, the matching of letter-like forms test, the block design (level) sub-test and the word reading test, all taken from the British Ability Scales (Elliott *et al*, 1983). Bradley & Bryant's (1983) phonological oddity task was administered to assess the children's phonological processing skills.

6.3 Procedure:

Each stage of the study was carried out over three testing periods so as to avoid over-tiring the children and risk losing their attention.

6.3.1 Testing period 1: Pegboard task :

During the first stage of testing the children were called by the experimenter to perform the pegboard task in groups of 4 or 5 although only one child actually performed the task at any time while the others watched. This was done to familiarise the children with the testing procedure and to minimise their natural apprehension. Prior to the administration of the pegboard task the children were asked to identify their left hands and their right hands, with corrective feedback given where necessary. The task was subsequently undertaken by each child three times with the left hand and three times with the right hand (see **Chapter 5**).

At subsequent stages, and through the second and third periods of the first stage, the children were seen individually in a quiet room away from the classroom. At the start of the second period the children were informed that they would be given a number of games to try, but that the games were for children of all ages; some would be easy to do while others may be difficult. If they felt unable to solve any of the problems the children were instructed to inform the experimenter who would move onto the next item.

6.3.2 Testing period 2:

During this period, the block design, the matching of letter-like forms and the recall of digits tasks were administered (see **Chapter 5**).

6.3.3 Testing period 3:

Finally, the children were asked to perform the phonological discrimination task, the word reading task and the Annett Hand Preference questionnaire (see **Chapter 5**).

While the tests administered in each period were the same for all of the children, the order of presentation of the tests was randomised between subjects.

6.4 Data Reduction:

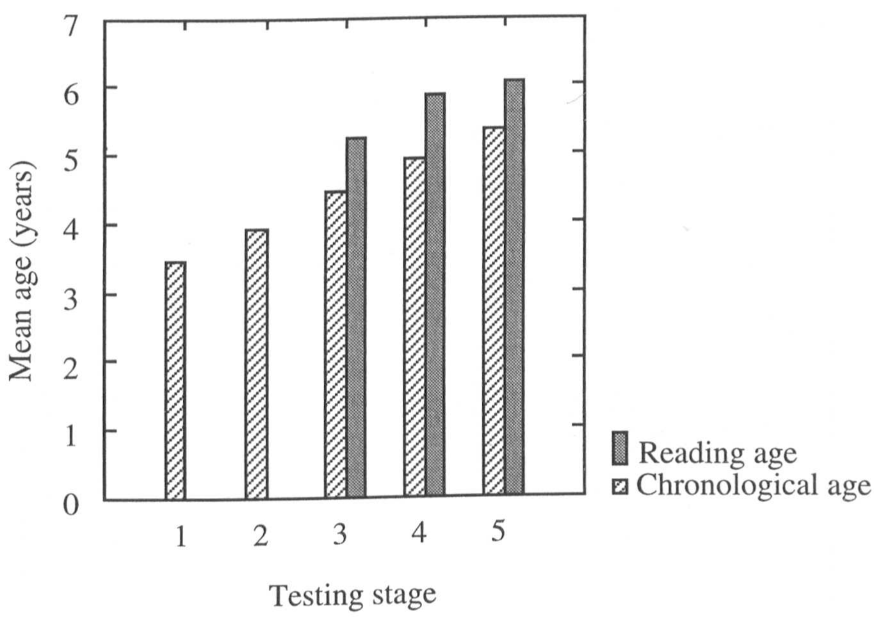
The data were analysed using multiple regression statistics, multivariate analyses of covariance and partialled time-lag correlations. Greenhouse-Geisser conservative degrees of freedom were taken to determine significance levels of all statistical calculations (Greenhouse & Geisser, 1959) and Tukey's test for Honestly Significant Differences (HSD) was employed as a post hoc test of significant pairwise comparisons.

6.5 Results:

6.5.1 Sample characteristics:

Descriptive statistics for the sample can be seen in **table 6.1**. Analysis of the chronological-ages and reading-ages of the children at each stage of testing yielded a significant main effect of chronological-age [F (4, 412) = 881.43; p < 0.005; see **figure 6.1**]. As the children were unable to read until stage 3 of the study, variance in the scores from stages 1 and 2 was zero. Therefore only reading-age scores from stages 3, 4 and 5 were analysed. These analyses revealed a main effect of reading ability [F (2, 204) = 184.10; p < 0.005], showing significant improvements in reading skill between each stage of testing included in the analyses (all p values < 0.005).

Figure 6.1 Chronological- and reading-ages at each stage of testing.



6.5.2 Hand skill and hand preference measures:

Analyses of variance performed on the pegboard completion times (see **table 6.1** and **figure 6.2**) revealed a significant main effect of testing session for both the left hand [F (4,400) = 189.68; p < 0.005] and the right hand [F (4,400) = 204.38; p < 0.005].

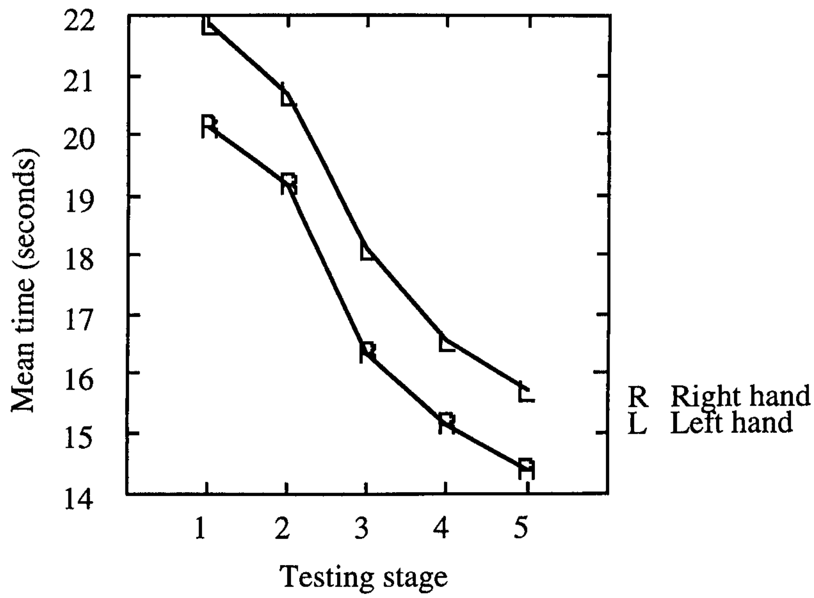
Table 6.1. Mean chronological-ages, reading-ages and handedness performance, with standard errors in brackets

Testing stage (n =)	Chronological-age: years	Reading-age: years	Peg Left: seconds	Peg Right: seconds	Pegboard Laterality Indices	Hand Preferences
1	3.46	.	21.85	20.14	4.10	3.23
(142)	(±0.04)		(±0.27)	(±0.26)	(±0.48)	(±0.16)
2	3.90	.	20.67	19.18	3.60	3.01
(142)	(±0.03)		(±0.29)	(±0.25)	(±0.59)	(±0.17)
3	4.46	5.22	18.10	16.35	5.00	2.61
(108)	(±0.04)	(±0.08)	(±0.21)	(±0.18)	(±0.52)	(±0.19)
4	4.92	5.85	16.54	15.14	4.35	2.72
(107)	(±0.03)	(±0.07)	(±0.17)	(±0.17)	(±0.56)	(±0.19)
5	5.36	6.04	15.70	14.39	4.42	2.61
(104)	(±0.04)	(±0.07)	(±0.17)	(±0.17)	(±0.56)	(±0.19)

Key: Reading age = as determined by the British Ability Scales Word Reading test; Peg Left = left hand mean completion time on the pegboard; Peg Right = right hand mean completion time on the pegboard; Pegboard Laterality Indices = ((peg left-peg right)/(peg left+pegright)) * 100; Hand Preferences = score on the Annett Hand Preference questionnaire.

Post hoc analysis of these results indicated that both hands became significantly faster at each successive stage of testing (all p values < 0.05).

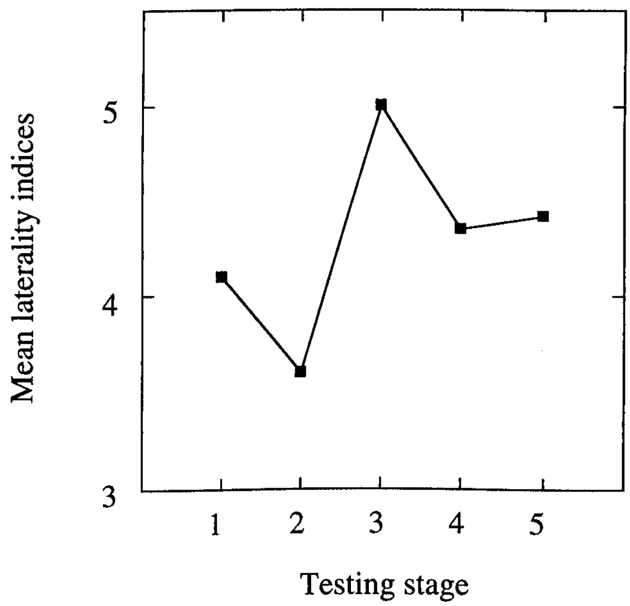
Figure 6.2. Mean left and right hand completion times on the pegboard task.



Significant main effects of hand were also obtained at each stage (first [F (1,140) = 68.34; p < 0.005], second [F (1, 140) = 40.42; p < 0.005], third [F (1,106) = 92.38; p < 0.005], fourth [F (1, 105) = 63.25; p < 0.005] and fifth [F (1, 102) = 58.80; p < 0.005] testing stages). In each instance this effect reflected the faster pegboard completion time by the right hand than by the left hand.

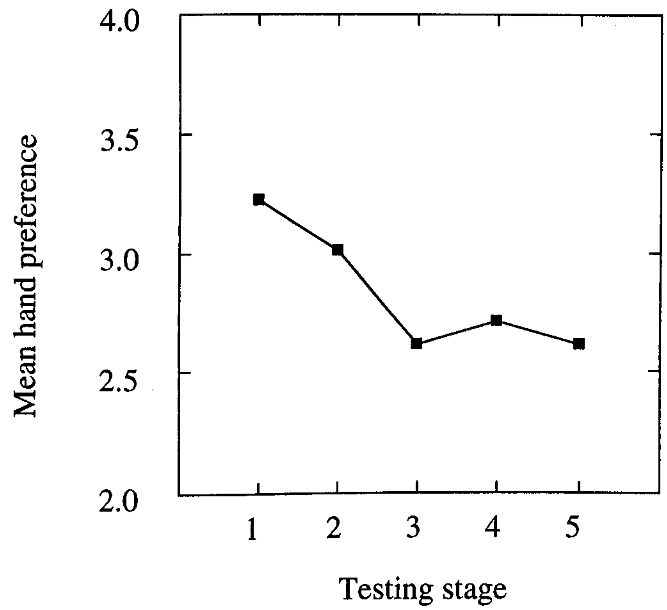
A comparison of the actual increases in skill in the left and right hands between each adjacent stage revealed a trend for greater increases in left hand skill than in right hand skill between stages 1-2, 3-4 and 4-5. Between stages 2 and 3, however, right hand skill increased significantly more than left hand skill [F (1, 105) = 5.16; p = 0.03]. These effects are illustrated in **figure 6.3**.

Figure 6.3. Pegboard laterality indices for the children at each stage of testing (the greater the left hand skill, relative to the right, the lower the laterality index).



The only significant effect to emerge from analysis of the hand preference data was found between stages 2 and 3 [$F(1, 105) = 8.68$; $p < 0.005$]. This effect reflected the children's greater right hand preferences at the third testing stage than at the second, as plotted in **figure 6.4**.

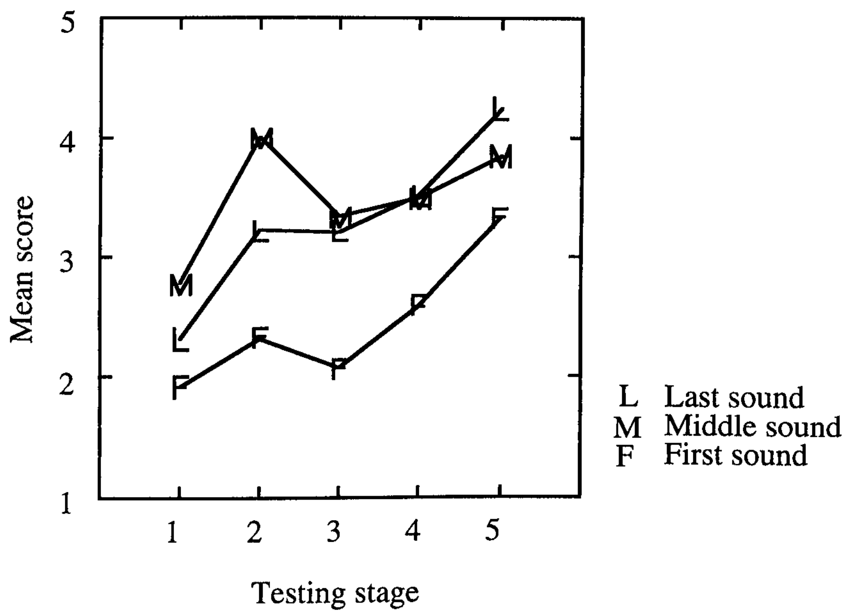
Figure 6.4. Hand preference categories at each stage (the lower the hand preference value the greater the preference for the right hand).



6.5.3 Psychometric measures:

Analyses of variance performed on the longitudinal data from the phonological oddity task highlighted significant main effects of both testing stage and condition (first-, middle- or last-sound-different; see **table 6.2**). As may be seen in **figure 6.5** the children's performance on the phonological oddity task generally increased over time in all three conditions (first- [$F(4, 396) = 23.16$; $p < 0.005$], middle- [$F(4, 396) = 11.34$; $p < 0.005$] and last- [$F(4, 396) = 16.49$; $p < 0.005$] sound different).

Figure 6.5. Phonological oddity scores (in the first-sound-, middle-sound- and last-sound-different conditions) produced by the children at each stage of testing (maximum possible scores of 8).



Post hoc testing of the results for the first-sound-different condition revealed that the scores at the first testing stage were significantly lower than at the fourth ($p = 0.02$) and fifth ($p < 0.005$) sessions and that the scores at the second ($p < 0.005$), third ($p < 0.005$) and fourth ($p = 0.02$) stages were also lower than at the final stage.

Table 6.2. Mean scores (with standard errors) on the psychometric test battery at each stage of testing.

Stage	**First-sound-different**	**Middle-sound-different**	**Last-sound-different**	**Digit span**	**Block design**	**Matching of letter-like forms**
1	1.92	2.78	2.32	3.18	1.18	4.17
	(±0.14)	(±0.15)	(±0.13)	(±0.31)	(±0.09)	(±0.21)
2	2.33	4.00	3.22	3.36	1.31	5.44
	(±0.10)	(±0.11)	(±0.13)	(±0.27)	(±0.10)	(±0.26)
3	2.07	3.33	3.21	3.63	1.99	6.90
	(±0.09)	(±0.12)	(±0.16)	(±0.34)	(±0.19)	(±0.32)
4	2.59	3.49	3.51	3.99	2.99	9.25
	(±0.12)	(±0.16)	(±0.19)	(±0.37)	(±0.22)	(±0.31)
5	3.33	3.85	4.25	4.03	4.56	11.02
	(±0.17)	(±0.18)	(±0.22)	(±0.34)	(±0.28)	(±0.31)

Key: First-sound-different = Bryant & Bradley first-sound-different condition; Middle-sound-different = Bryant & Bradley middle-sound-different condition; Last-sound-different = Bryant & Bradley last-sound-different condition.

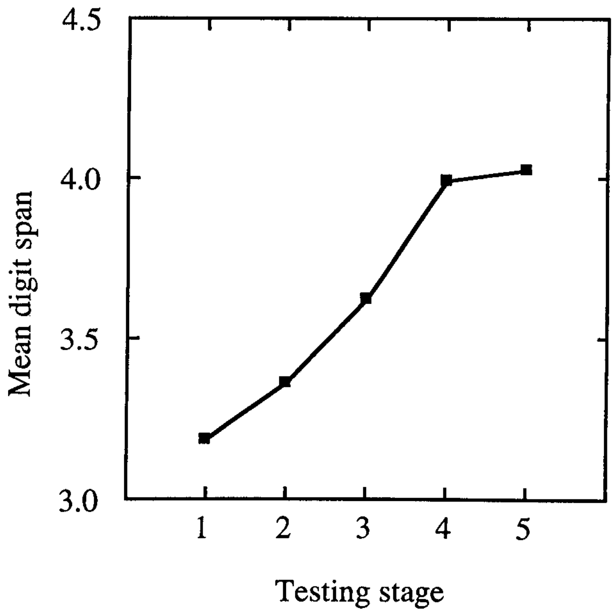
The scores for the middle-sound-different condition showed that the children performed significantly poorer on the task at the first testing stage than at the second ($p < 0.005$), fourth ($p = 0.02$) or fifth ($p < 0.005$) stages but not the third.

Finally, as is apparent in **figure 6.5**, post hoc testing of the scores in the last-sound-different condition revealed significantly poorer ability at the first time of testing than at the second ($p < 0.005$), third ($p = 0.007$), fourth ($p < 0.005$) or fifth ($p < 0.005$) times, and lower scores at each of the second ($p = 0.002$), third ($p < 0.005$) and fourth ($p = 0.03$) testing stages than at the fifth.

Significant within-subjects effects of condition were obtained at each testing stage. For stage 1 this result reflected the children's better performance in the middle-sound-different condition than in the first-sound-different condition ($p = 0.001$); for the stage 2 results post hoc testing revealed better performance in the middle- ($p < 0.005$) and last- ($p < 0.005$) sound-different conditions than in the first-sound-different condition, and significantly better performance in the middle-sound-different condition than in the last-sound-different condition ($p = 0.002$). At the third stage of the study the children were significantly more accurate in the middle- and last-sound-different conditions than in the first-sound-different condition (both p values < 0.005); this pattern of results was again found in the fourth testing session (both p values < 0.005). By the final session the only significant difference in accuracy was found between the first-sound-different and last-sound-different conditions ($p < 0.005$), with the better performance in the latter condition.

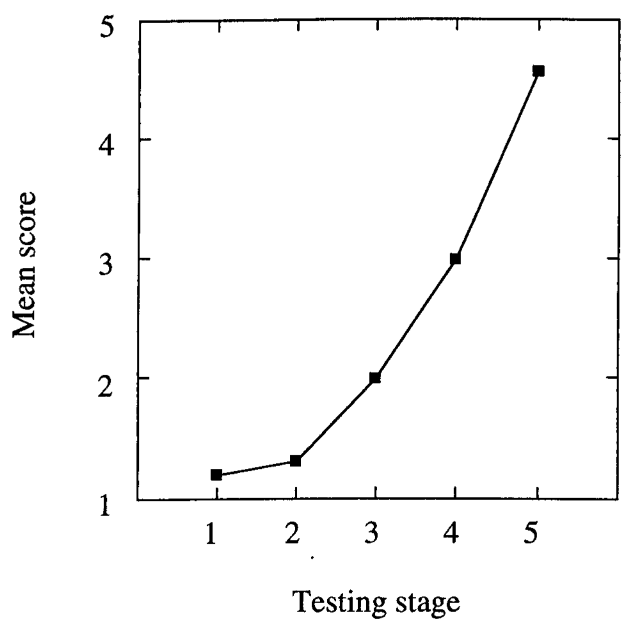
Analysis of the data from the digit span task (see **table 6.2**) revealed a significant effect of testing session [$F(4,400) = 111.87$; $p < 0.005$]. As **figure 6.6** shows, this effect reflects significant improvements in the performance of this task between every stage (all ps < 0.005), except from the fourth to the fifth testing sessions ($p > 0.05$) where the subjects' increase in performance appears to plateau.

Figure 6.6. Performance of the children on the digit span task at each stage of the study.



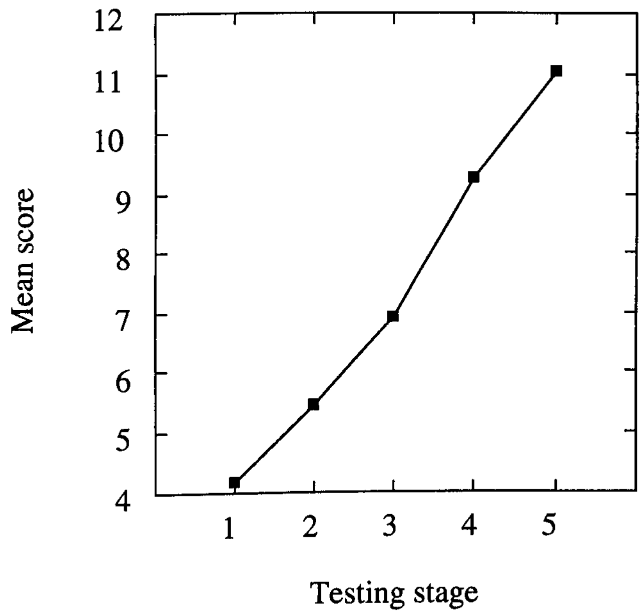
A significant effect of testing stage also emerged from analysis of the block design data [$F(4,400) = 113.39$; $p < 0.005$]. This effect reflected significant increases in the total number block designs reproduced correctly by the children between every stage from the second stage onwards (all p values < 0.005), as seen in **figure 6.7**.

Figure 6.7. Scores for the children on the block design task



Analysis of the data from the matching of letter-like forms task (**table 6.2**) again yielded a significant effect of testing stage [F (4,400) = 177.32; p < 0.005: illustrated in **figure 6.8**]. Significant improvements in accuracy were made on this task between every stage (all p values < 0.005).

Figure 6.8. Scores on the matching of letter-like forms subtest at each stage of testing (out of a maximum of 16).



6.5.4 Is it possible to predict reading ability on the basis of preceding and concurrent neuropsychological abilities?

To determine which, if any, of the variables predicted reading ability at each stage, the data were applied to multiple regression statistics (significant predictors are displayed in **table 6.3**). Unsurprisingly, entering left and right hand pegboard scores into the regression calculations, in addition to the pegboard laterality indices, resulted in multicollinearity (i.e. a high degree of inter-correlation between predictor variables entered into a multiple regression), and reduced the stability of the equation. The individual hand skill scores were dropped, therefore, from subsequent analyses in favour of the laterality indices.

Table 6.3. Significant predictor variables for reading ability at each stage of testing (with regression coefficients).

	Reading 3 predicted by:	**Reading 4 predicted by:**	**Reading 5 predicted by:**
Stage 1 predictors:	Digit span (0.07)** ---------->	Digit span (0.17)* ----------->	Digit span (0.30)**
		Letters (0.21)*	
Stage 2 predictors:	BBM (0.13)* ---------------->	BBM (0.33)* ---------------->	BBM (0.42)*
		Digit span (0.17)* ----------->	Digit span (0.26)**
		Letters (0.21)** --------------->	Letters (0.26)*
	Blocks (0.26)**		
Stage 3 predictors:		BBF (0.48)* ---------------->	BBF (0.71)*
		Reading (1.14)** -------------->	Reading (1.29)**
		Letters (0.15)* --------------->	Letters (0.22)*
	Blocks (0.15)**		
Stage 4 predictors:		Digit span (0.14)* ----------->	Digit span (0.14)*
		BBM (0.43)*	
			Reading (0.95)**
Stage 5 predictors:			BBL (0.37)*

Key: BBF = Bradley & Bryant first-sound-different condition; BBM = Bryant & Bradley middle-sound-different condition; BBL = Bryant & Bradley last-sound-different condition; Digit span = digit span score; Blocks = block design ability; Letters = matching of letter-like forms; Reading = word reading ability. The dashed arrows (-->) connect variables which significantly predict reading ability across more than one stage of the study. * $p \leq 0.05$; ** $p < 0.005$.

The intention of the present study was to investigate the cognitive context within which literacy develops in children. It was not an intention of this study to investigate differences between the cognitive and literary competencies of children divided according to sex. In line with many such studies (for example, Wimmer *et al*, 1991; Stahl & Murray, 1994; Bosman & de Groot, 1995), the present one collapsed the sample across sex. The potential influence of this variable cannot be disregarded, however, so it was partialled out of the data in all analyses. Although all of the remaining handedness and psychometric measures were entered into the analyses as dependent variables, invariance in the reading scores from the first two testing sessions (while the children were still unable to read) meant that only reading scores from stages 3, 4 and 5 were entered into the regression calculations.

Table 6.3 shows that digit span at stage 1 ($r = 0.07$; $p < 0.005$), score in the middle-sound-different condition of the phonological oddity task ($r = 0.13$; $p = 0.01$) and block design ability ($r = 0.26$; $p < 0.005$) at stage 2, and block design ability at stage 3 ($r = 0.15$; $p < 0.005$) significantly predicted reading ability at stage 3.

Stage 4 reading ability was predicted by digit span ($r = 0.17$; $p = 0.05$) and by matching of letter-like forms ability ($r = 0.21$; $p = 0.05$) at stage 1, by score in the middle-sound-different condition of the phonological discrimination task ($r = 0.33$; $p = 0.04$), by digit span ($r = 0.17$; $p = 0.05$) and by ability on the matching of letter-like forms task ($r = 0.21$; $p = 0.01$) at stage 2. Stage 3 variables which significantly predicted stage 4 reading ability were phonological oddity first-sound-different condition score ($r = 0.44$; $p = 0.05$), reading ability ($r = 1.08$; $p < 0.005$) and matching of letter-like forms score ($r = 0.15$; $p = 0.05$). Within the fourth testing stage the reading score was predicted by digit span ($r = 0.14$; $p = 0.04$) and by performance in the middle-sound-different condition of the phonological oddity task ($r = 0.43$; $p = 0.01$).

The children's reading ability at stage 5 was significantly predicted by digit span at stages 1 ($r = 0.30$; $p < 0.005$), 2 ($r = 0.26$; $p < 0.005$) and 4 ($r = 0.14$; $p = 0.04$); by accuracy in the first-sound-different condition of the phonological oddity task at stage 3 ($r = 0.71$; $p = 0.01$); by the score in the middle-sound-different condition of this task at stage 2 ($r = 0.42$; $p = 0.03$), and in the last-sound-different condition at stage 5 ($r = 0.37$; $p = 0.02$); by matching of letter-like forms ability at stages 2 ($r = 0.26$; $p = 0.04$) and 3 ($r = 0.22$; $p = 0.04$); and by reading ability at stages 3 ($r = 1.29$; $p < 0.005$) and 4 ($r = 0.95$; $p < 0.005$).

Correlation coefficients between each pair of variables at each stage are found in **Appendix 13**.

6.5.5. Does the relationship between these variables change significantly over time?

While these analyses highlight a relationship between the different variables across the duration of the longitudinal study, they do not establish the direction of causality. Does phonological memory (as indexed by the measure of digit span), for example, lead to improved reading or do increasing reading skills serve to enhance digit span? To investigate this, partialled cross time-lag correlations were calculated on the data. The advantage of employing partialled cross time-lag correlations over simple cross-lagged correlations is that this more sophisticated statistical procedure controls for pre-existing influences between the variables at time 1 and at time 2, thus avoiding the reporting of fallacious relationships (Type 1 errors).

It may be, for example, that measure A is a critical determinant of measure B within testing stage 1. Any relationship between measure B at stage 1 and measure A at stage 2 may, therefore, merely be a reflection of the indirect contribution of measure A at stage 1 to measure A at stage 2, while revealing nothing about the actual influence of measure B on measure A at the adjacent stage of testing. This possibility is removed in the present study by partialling out the earlier score on each outcome measure prior to the calculation of the partialled time-lag correlations.

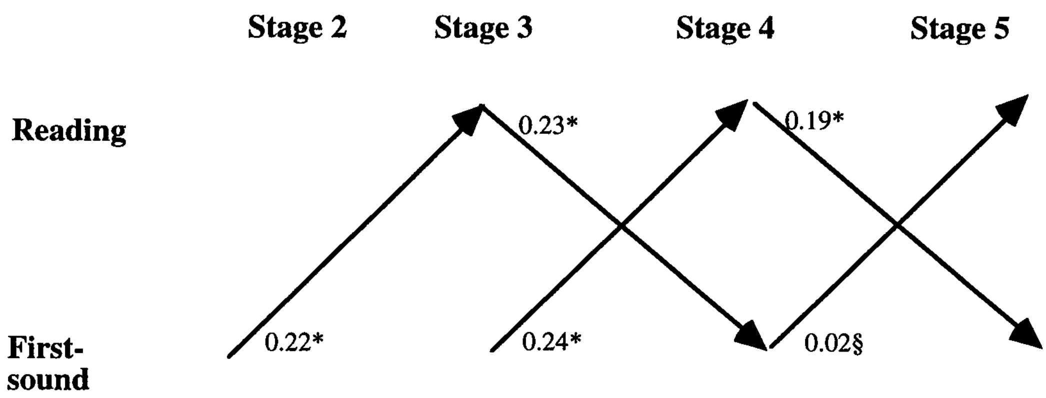
These partialled time-lag correlations were calculated in two waves to address the two theoretical perspectives of this study. Firstly the hand skill laterality indices from each stage of testing were paired with each of the psychometric measures from the subsequent stage to investigate the possibility that handedness may provide a neuropsychological index of the cognitive context in which reading develops. Unfortunately hand skill failed to emerge as a significant predictor of any of these measures at any stage of the study.

The second wave of analyses aimed to investigate the emerging relationships between reading skill and each of the cognitive and psychophysiological variables directly. Each of these variables was paired individually with reading ability across contiguous stages of testing. Once again it should be noted that as reading ability was only apparent from stage 3, the partialled time-lagged correlations have only been computed using the cognitive and handedness variables from stage 2 onwards.

6.5.5 (a). Reading ability and phonological processing skills:

Figure 6.9 shows that even using this conservative statistical procedure significant positive relationships emerged between alliterative awareness and adjacent reading ability. Stage 2 ability on the phonological oddity task was positively related to stage 3 reading ($r = 0.22$; $p \leq 0.05$) and stage 3 phonological awareness was positively related to stage 4 reading ($r = 0.24$; $p = 0.01$).

Figure 6.9. Partial time-lag correlations between score on the first-sound-different condition of the phonological oddity task and reading ability.

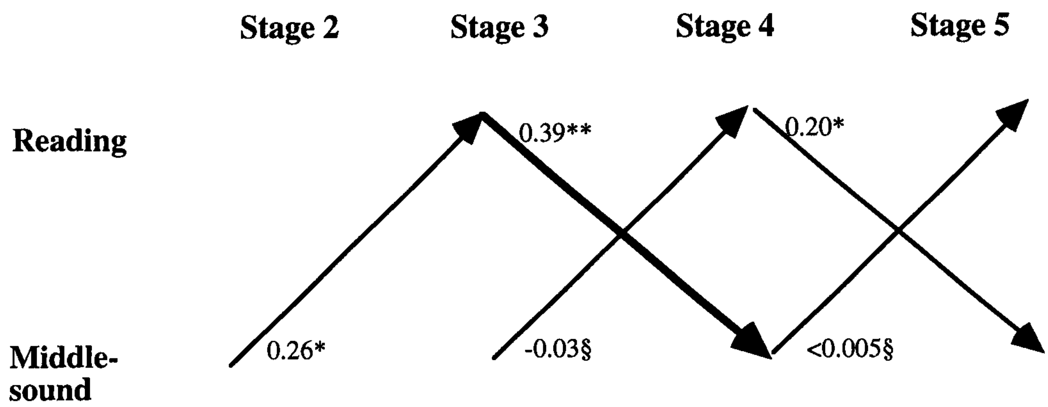


Key: § p > 0.05; * p ≤ 0.05.

Once the child has acquired preliminary reading skills, however, the phonological awareness measure no longer appears to exert an influence on subsequent reading ability, although reading ability continues to influence alliterative awareness at each stage (stage 3 reading to stage 4 alliterative awareness: $r = 0.23$; $p = 0.02$; stage 4 reading to stage 5 phonological ability: $r = 0.19$; $p = 0.05$).

As can be seen in **figure 6.10**, the data from the middle-sound-different condition of the phonological oddity task revealed a similar pattern to the one observed for the first-sound-different condition. The strongest relationship between ability in the middle-sound-different condition of the phonological oddity task and reading competence runs from the latter measure at stage 3 to the former at stage 4 ($r = 0.39$; $p < 0.005$). This relationship continues from stage 4 to stage 5 but is diminished in strength ($r = 0.20$; $p = 0.04$). Turning to the converse relationship, phonological awareness at stage 2 significantly predicted the earliest reading skills (at stage 3: $r = 0.26$; $p \leq 0.05$), but this relationship was not sustained across subsequent stages of the study.

Figure 6.10. Time-lagged correlations between score in the middle-sound-different condition of the phonological task and reading score.

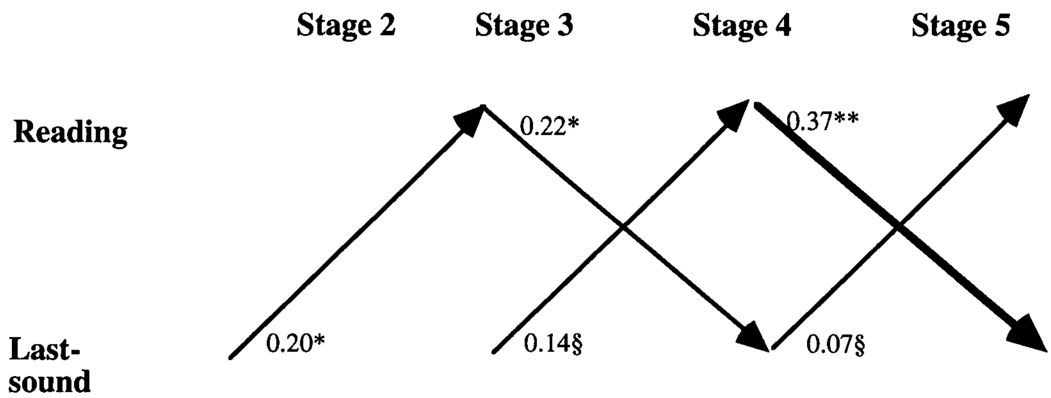


Key: § $p > 0.05$; * $p \leq 0.05$; ** $p < 0.005$. The line in bold indicates that this partial correlation is significantly greater than the cross-lagged partial correlation.

As indicated by the bold arrow in **figure 6.10**, the relationship between stage 3 reading ability and stage 4 phonological awareness is significantly greater than the converse relationship ($t = 3.29$; $p < 0.005$).

A comparison of the relationship between reading ability and score in the last-sound-different condition of the phonological oddity task (**figure 6.11**) again reveals that the stronger relationships run from reading to subsequent phonological awareness than in the opposite direction.

Figure 6.11. Time-lagged correlations between reading ability and score in the last-sound-different condition of the phonological oddity task.



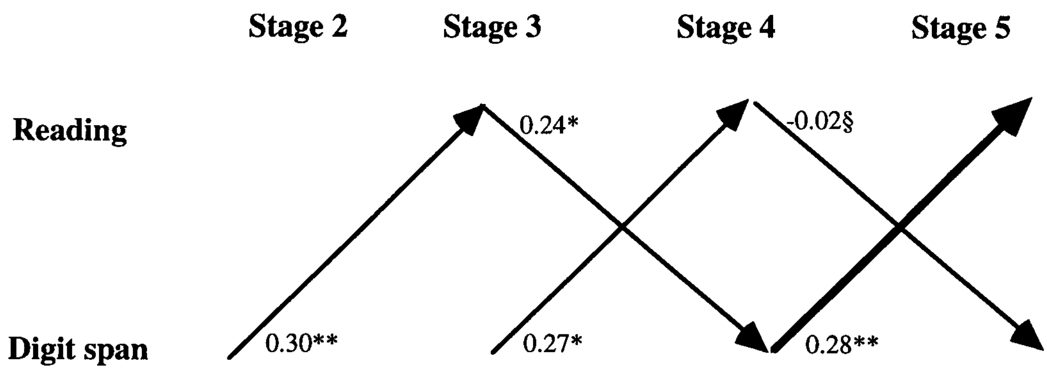
Key: § $p > 0.05$; * $p \leq 0.05$; ** $p < 0.005$. The line in bold indicates that this partial correlation is significantly greater than the cross-lagged partial correlation.

Stage 3 reading ability is related to stage 4 competence on the phonological awareness task ($r = 0.22$; $p = 0.02$; see **figure 6.11**). This relationship is strengthened by the next stage of testing such that stage 4 reading skill significantly predicted the children's ability to discriminate between words on the basis of their ultimate sounds ($r = 0.37$; $p < 0.005$). As indicated by the bold arrow in **figure 6.11**, the relationship between stage 4 reading ability and stage 5 phonological discrimination ability was significantly greater than the relationship from stage 4 phonological ability to ultimate reading skill ($t = 2.31$; $p = 0.02$). Once again phonological awareness at stage 2 significantly predicted reading ability at stage 3 ($r = 0.20$; $p \leq 0.05$), but not at later stages.

6.5.5 (b). Memory capacity and reading development:

Figure 6.12 shows that phonological memory capacity at each stage is significantly related to later reading ability even when current reading ability is controlled for.

Figure 6.12. Time-lagged correlations between digit span and reading ability.



Key: § p > 0.05; * p ≤ 0.05; ** p < 0.005. The line in bold indicates that this partial correlation is significantly greater than the cross-lagged partial correlation.

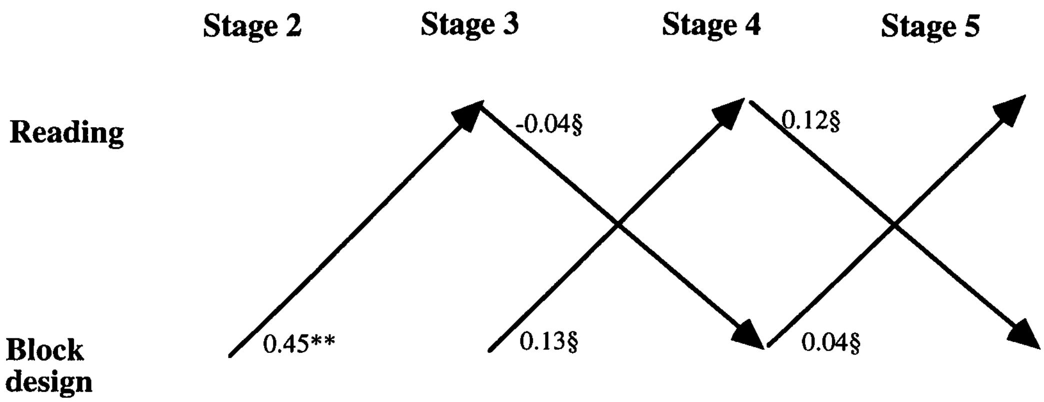
It is clear from **figure 6.12** that digit span is a strong predictor of reading ability across each stage of this study: from stage 2 digit span to stage 3 reading ($r = 0.30$; $p < 0.005$), from stage 3 to stage 4 ($r = 0.27$; $p = 0.01$; **figure 6.12**), and from stage 4 digit span to reading ability at the final stage of testing ($r = 0.28$; $p < 0.005$). The relationships running in the opposite direction are less clear. Whereas the earliest measure of reading significantly relates to digit span at the penultimate stage ($r = 0.24$; $p = 0.01$), this relationship is not sustained between stage 4 reading skill and stage 5 digit span ($p > 0.05$). In fact, the relationship between stage 3 reading ability and stage 4 digit span is significantly greater than the corresponding relationship between these two measures at the next stage of the analysis ($t = 1.93$; $p = 0.05$). Unsurprisingly, the correlation between penultimate digit span and subsequent reading ability is significantly greater than the converse relationship between reading ability and digit span at these last two stages of the study ($t = -2.20$; $p = 0.03$).

6.5.5 (c). Reading development and visual processing ability:

Both measures of visual processing ability taken at the second stage of the study (see **figures 6.13** and **6.14**) significantly predicted the emergence of reading skills at the third stage (block design ability: $r = 0.45$; $p < 0.005$; matching of letter-like forms: $r = 0.19$; p

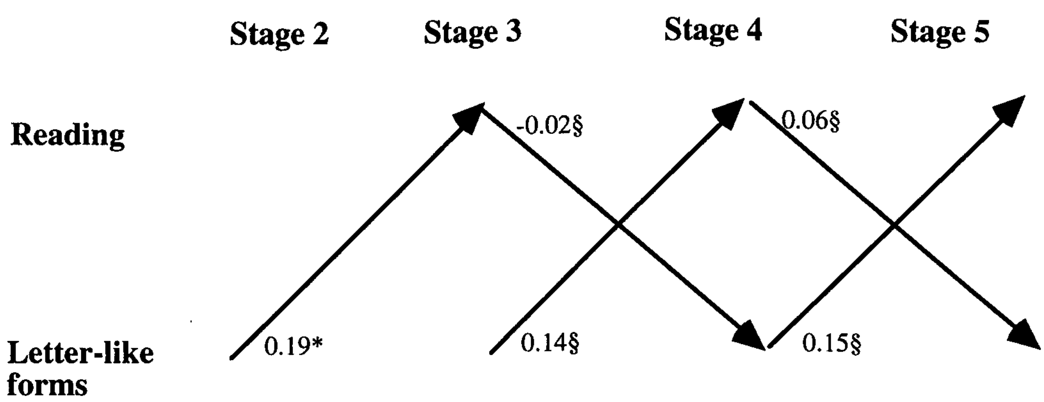
≤ 0.05). No further significant relationships were found between the children's performance on these measures and their reading ability across the remainder of the study (all p values > 0.05).

Figure 6.13. Partial time-lagged correlations between score on the block design and reading tests.



Key: § p > 0.05; * p ≤ 0.05.

Figure 6.14. Partial time-lag correlations between matching of letter-like forms scores and reading ability.

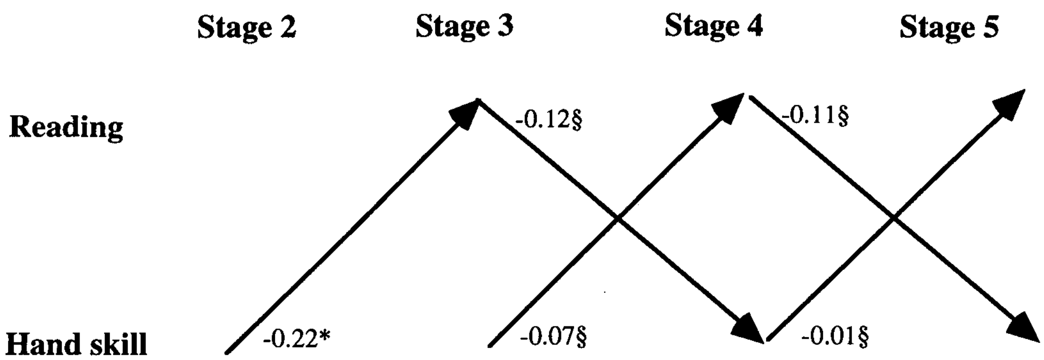


Key: § p > 0.05; * p ≤ 0.05.

6.5.5 (d) Reading skill and handedness:

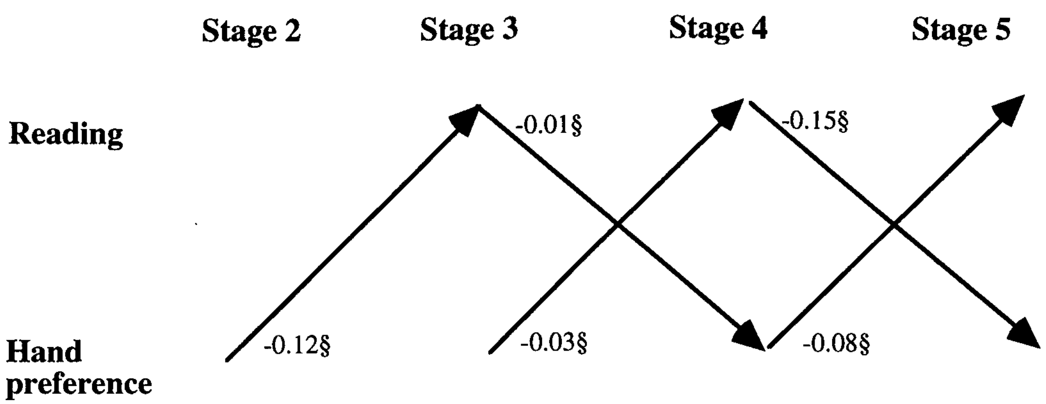
As may be seen in **figure 6.15**, the only significant relationship between handedness and reading ability was found in terms of hand skill between the second and third stages of the study. This relationship is negative, indicating that the greater the pre-literate child's right hand skill the better their emergent reading ability at stage three. No other significant relationships were found between either hand skill (**figure 6.15**) or hand preference (**figure 6.16**) and adjacent reading ability across the study.

Figure 6.15. Partialled time-lag correlations between hand skill (pegboard laterality indices) and reading ability



Key: § $p > 0.05$; * $p \leq 0.05$.

Figure 6.16. Time-lag correlations between hand preference and reading skill



Key: § $p > 0.05$.

6.6 Discussion of results:

One aim of the present study was to investigate the relationship between emerging reading skills and the cognitive profiles (phonological awareness, verbal memory and visual perceptual skills) of children from an initial state of pre-literacy to a state, 2 years later, of early reading competence. A further aim was to index the psychophysiological substrate of reading development as assessed indirectly by measures of hand skill and hand preference.

6.6.1 Behavioural and cognitive measures: age-related changes:

6.6.1 (a) The emergence of literacy

None of the children showed any sign of reading ability at the first testing stage. Thus this sample conformed to Wagner & Torgesen's (1987) proposal that the maximally informative longitudinal study should commence with a sample of children objectively proven to be non-readers. By the time of the third testing session the children had moved from the nursery schools into full time formal schooling, so it was unsurprising to find that by this session most of the children could read at least some of the words presented to them; indeed the children's reading ages were found to slightly exceed their chronological ages. This apparent inconsistency between the children's chronological-ages and reading-ages should offer no cause for concern. The notion of a "reading-age" has been criticised in the literature as representing a fairly arbitrary measure of a child's actual reading ability (just as IQ has been criticised as a measure of mental capacity; see Beard, 1987; Flynn, 1987; Adams, 1990 for a discussion). The current investigation, therefore, presents the reading ages of the sample merely as a general indication of its developing literary competence over time. From these measures it is apparent that having emerged at stage three the children's reading skills continue to increase steadily at approximately the same rate as their chronological ages.

6.6.1 (b) Changes in handedness over time

The children, who were predominantly dextral from the outset on the basis of their hand preferences, showed significantly greater right than left hand skill on the pegboard task at each stage of testing. Overall the children's performance on the task increased (the time taken to complete the task decreased) between every testing session. This developmental increase in hand skill, in both hands, has previously been reported from the age of 2 1/2 years, with maximal skill displayed from the late teenage years (Fennel *et al*, 1983; Curt, Maccario & Dellatolas, 1992). This would appear, therefore, to reflect a general maturation effect.

In accordance with expectations, the sample showed a bias in favour of the right hand at each testing stage. Although no significant increase in dextrality was observed over the study as a whole (as also reported by Roskowski, Snelbecker & Sacks, 1980; Kilshaw & Annett, 1983; Curt *et al*, 1992), an increase in skill of the children's right hands significantly exceeded that of their left hands (which also increased, but to a lesser degree) between the second and third stages. This finding is reflected in the positive hand skill laterality indices which again indicate the general trend towards right hand dominance. Between stages 1 and 2 and between stages 3 and 4 there appears to be a tendency for the children's left hand skill to increase relative to their right hand skill, while between the last two testing sessions the two hands appear to increase in skill at approximately the same rate. It is the significant change in hand skill between stages 2 and 3 of the study which is of particular interest. During this period the positive spike in the graph showing the pegboard laterality indices (**figure 6.3**) indicates a sudden move towards increased dextrality. On the assumption that measures of hand skill provide an indication of cerebral development (Obrzut, 1989; Annett, 1992b) it is possible that this increase in skill may reflect an augmentation in cortical maturation, particularly in the left hemisphere, during the period when children begin to acquire early literacy skills.

Regarding hand preference, the only significant change across the period of the present study was found between stages 2 and 3. In accordance with the hand skill measure this change reflects a move towards significantly greater dextrality (the smaller the hand preference scores the greater the reliance upon the right hand). The children's hand preferences were relatively stable after the third testing session except for a non-significant fluctuation between the third and fourth stages which failed to change the sample's overall hand preference from that of predominantly dextral with weak to mild sinistral tendencies.

These results are consistent with previous investigations of children's developmental hand preferences. Kilshaw and Annett (1983), for example, report finding no significant changes in hand preference in the 3 1/2 to 15 year old children included in their cross-sectional study. It is possible, however, that subtle differences in preference (such as the one detected in the present study) may have been missed by Kilshaw and Annett. These researchers determined hand preference in their sample on the basis of an abridged version of the A.H.Q. (including only two primary actions). Further support for the relative invariance of hand preference is offered (Ramsay, Campos & Fenson, 1979; Young, 1982) but Young (1982) cautions that a consistent preference may only emerge in response to tasks requiring some degree of skill for their completion; easier tasks may, he warns, elicit fairly arbitrary preferences. Curt *et al* (1992), however, required the children in their cross-sectional study to perform a range of uni-manual actions (similar to those used in the present study) and found age-related increases in dextral hand preference only amongst their "strong right-handers". In support of the present finding this change was greatest between the ages of 3 1/2 and 4 1/2 years.

Thus, it would appear that children's hand preferences are relatively well established at an early age. It is entirely possible that the increased preference for the right hand observed in children around the age of 3-4 years (in the present study and in the study by Curt *et al*, 1992) reflects nothing more than a training effect. Increased practice using right hand (for holding a pencil, using scissors or holding a tennis racket, for example) in the early stages of school may increase a child's preference for the right hand (Provins & Magliaro, 1993). Whether this is the case, or whether observed changes in hand preference are actually indicative of underlying physiological development, possibly related to the acquisition of early literacy skills, is impossible to determine on the basis of existing evidence.

6.6.1 (c) Phonological awareness and development

Significant improvements over time were observed in the children's performance of all three conditions of the phonological oddity task although different rates of increase were observed across the three conditions. Within the first-sound-different condition the children's performance remained relatively constant until a sudden improvement from the fourth testing session onwards. A significant improvement in the performance of the middle-sound-different condition was found at the second stage of testing, although performance thereafter failed to change significantly; in fact, the mean scores obtained in this condition declined slightly after the second testing stage and then failed again to reach the stage two level. The children's ability to identify words which differed on the basis of their last sounds also increased significantly between the first and second testing sessions, and again at the final stage.

Significant differences were found over the three conditions of this task. Overall performance was significantly poorer in the first-sound-different condition than in either of the other two conditions until the fourth stage of testing. By the final stage performance in the first-sound-different condition had increased dramatically relative to its previous level, and was only significantly inferior to the children's performance in the last-sound-different condition. The only significant difference between the middle-sound- and last-sound-different conditions emerged at the second stage of testing; performance in the former condition was superior to that in the latter.

These scores at first glance appear to indicate a lower level of performance by the current sample than by children in previous studies. These discrepancies may be accounted for by methodological differences, however. The majority of studies employing the same paradigm as the present investigation have involved children older than those in the present study (Bradley, 1980; Snowling *et al*, 1986; Bowey & Patel, 1988). Previous investigations with children of a comparable age have generally involved a modification of the experimental design. These studies have, for example, only presented 3 words at a time for the children to distinguish between (Bradley & Bryant, 1983; Bryant *et al*, 1989; Bryant *et al*, 1990) and/ or have presented the stimuli in pictorial form (Bryant *et al*, 1989, 1990) in an attempt to reduce the memory requirements of the task for the younger children. Taking these differences into account the present results appear to be in line with expectation. The possible significance of these findings will be discussed later in the context of the children's cognitive development.

The poorer performance of these young children in the first-sound-different condition than in either of the other two conditions (as was also found by Bradley & Bryant, 1978, 1983) may be explained by the fact that whereas the non-target words in the middle- and last-sound-different conditions share the same vowel as well as the final consonant - that is, they rhyme (e.g.. <u>mop</u>, tap, <u>hop</u>, <u>lop</u>; <u>sun</u>, <u>gun</u>, rub, <u>fun</u>) - those in the first-sound-different condition do not. Therefore, simply by recognising the non-rhyming word of the four in each of the middle- and last-sound-different conditions, the child is able to accurately identify the odd-word-out, whether or not they are aware that the target word differs from the distractor words in terms of its middle or last sound. This process has described as "automatic similarity detection" (Wimmer *et al*, 1991), and likened to the mechanism whereby infants habituate to sequences of similar sounds and dis-habituate to a novel sound (Eimas, Siqueland, Jusczyk & Vigorito, 1971). This is not possible in the case of the first-sound-different condition in which none of the words rhyme (e.g. lick, lid, miss, lip), so forcing the child to focus on the structural components of the words in order to identify the odd-one-out. Whether this oddity detection is implicit or explicit it may still influence the acquisition of literacy skills by enabling children to read unknown words by analogy to known rhyming words (Goswami, 1986, 1988).

In surprising contrast to the present findings, Kirtley, Bryant, MacLean & Bradley (1989) report that a sample of 5 year old children, some of whom could and some could not read, performed significantly better on a task requiring them to identify the odd-word-out from a list of words of which one differed in the opening sound than on a task in which the odd-word-out differed in its end sound. In view of the explanation for the present study's findings offered above, Kirtley *et al*'s results at first glance appear paradoxical. This apparently inconsistent finding may be explained by the fact that, as with the first-sound-different words of the phonological oddity test, in Kirtley *et al*'s task the words which differed in their end sounds did not rhyme (e.g. mop, whip, lead), thus increasing the difficulty of this condition. A follow up study involving the presentation of end-sound-different words which did rhyme resulted in greatly increased accuracy in the identification of the odd-word-out (Kirtley *et al*, 1989).

That the difference between the 'rhyming' and 'non-rhyming' conditions of the present study is maximal at the second testing session (at the end of the nursery school year) may be explained by considering the development of a child's phonological awareness skills. Most children are exposed to nursery rhymes from birth, and in fact a large amount of time is spent in nurseries teaching children nursery rhymes and rhyming songs. It is not surprising, therefore, to find that sensitivity to rhyme develops easily and early in a child's life (Stanovich *et al*, 1984; Morais, Bertelson, Cary & Alegria, 1986; MacLean *et al*, 1987). The use of analogies in the teaching of reading and spelling skills builds on this early rhyme awareness by continuing to draw a child's attention to the end sounds of words (Marsh, Desberg & Cooper, 1977; Marsh *et al*, 1981; Goswami, 1986, 1988). This is especially true of phonics reading schemes, as employed in both of the schools from which these children were drawn.

Conversely, however, evidence suggests that sensitivity to alliteration does not develop as easily (Stanovich *et al*, 1984). Goswami (1986), for example, reports that 5 year olds are unable to utilise the onset of words to draw analogies between familiar and unfamiliar words. Bradley (1980) suggests that children may only attend to the start of words after having seen them in print, when learning to read and to spell. In the light of such evidence, the finding that children have less difficulty in differentiating between words which do or do not rhyme than in perceiving alliterative differences between words is hardly surprising (Adams, 1990).

6.6.1 (d) Developmental increases in phonological memory capacity

The steady increase in phonological memory span demonstrated over time may be accounted for in terms of a general intellectual maturation. A child's performance on memory recall tasks reflects not only their memory capacity but also attentional, perceptual and response mechanisms (Hulme & Roodenrys, 1995). Developmental increases in any of these abilities would contribute to the increasing overall ability of the children on the digit span task.

This finding accords with studies of working memory which have also reported maturational increases through childhood and adolescence (Pascual-Leon, 1970; Case *et al*, 1982; Hitch & Halliday, 1983) and with Siegel's (1994) report that both short term memory and working memory capacity increase with increasing age (although this latter study only tested subjects from the age of six years). An innovative study by Alp (1994) offers further support to the present findings, by reporting age-related increases in the (visual) working memory capacities of infants between 1 and 3 years.

It has been suggested that the performance of children on phonological memory tasks may reflect their knowledge of, and familiarity with, the stimuli used. Strong correlations have been reported, for example, between non-word repetition and vocabulary knowledge in children (Gathercole & Adams, 1993). This is not considered to be a plausible explanation for the present findings, however, because given the age of the children at the start of this study, the numbers used in the digit span task would all have been highly familiar. Support for this conclusion is provided in the form of non-significant correlations between children's digit spans and their ability to identify printed numbers (Gathercole & Adams, 1993, 1994).

An alternative explanation for this age-related increase in memory capacity is that it reflects maturational increases in the individual's articulation rate via a process of sub-vocal rehearsal (Baddeley *et al*, 1975; Hitch & Halliday, 1983; Hulme *et al*, 1984). The role played by speech skills in increasing memory span is well established in the literature, as discussed in **Chapter 2**. Research has shown, for example, that whereas memory span for digits is independent of articulation rate in children aged 3 years (Gathercole & Adams, 1993), 4 years (Gathercole & Adams, 1994) and 4 1/2 years (Gathercole, Adams & Hitch, 1994), rehearsal has been found to be in evidence by the age of 5 years (Gathercole & Adams, 1993). Similar developmental increases in memory capacity for words of varying length have been related by Hulme *et al* (1984) to speech rate in individuals from 4 years of age to adulthood.

This suggestion, that the relationship between memory span and speech rate is causal, is debatable. Recent studies indicate that age-related differences in memory span persist even when articulation rate is controlled for (Henry, 1991; Roodenrys *et al*, 1993). A revised explanation for this relationship, proposed by Hulme and Roodenrys (1995), is that age-related increases in memory capacity are the "by-product" of developmental increases in the processes underlying speech perception and production. In addition to naturally occurring developmental increases in speech perception and production abilities, practice in counting and in mental arithmetic once the child starts school will enhance its language mechanisms (Gathercole & Adams, 1994). The significant increases in memory span for numbers found at each stage of the present study should, therefore, come as no surprise.

The observation that the children's increases in memory capacity levelled off somewhat between the last two testing stages *is* surprising, however. This finding may be artifactual, due to some unknown factor exerting a temporary influence over the children's performance at the last testing session. Alternatively, it may be the result of an actual change in the children's abilities. The accuracy of these suggestions cannot be determined without exploring further changes in memory capacity over time.

6.6.1 (e) Age-related changes in visual processing ability

General maturational effects may also account for the finding that the children's performance on both of the measures of visual perception (the matching of letter-like forms and the block design tasks) generally increased across each stage of the study. Only the increase in block design performance between the first two stages of the study failed to emerge as significant. This latter finding may be explained as reflecting a floor effect across the first two testing sessions. The block design task was developed for use with children from the age of 4 years; the children in the present study had a mean age of 3 1/2 years at the first time of testing, and indeed, they initially exhibited some difficulty in the performance of this task. By the second stage the mean age of the sample was 4 years and thereafter the children's performance on this measure was in line with expectations.

6.6.2 Which of the neuropsychological measures predicted reading at each stage of development?

The variable which emerged from the present study as having the greatest predictive power over subsequent reading ability was phonological memory capacity (digit span). Memory capacity at the first stage of testing proved capable of predicting reading ability at the final testing stage, and phonological memory continued to predict later reading ability intermittently across the course of the study. This relationship between memory capacity and early reading ability is widely reported in the reading literature (Leather & Henry, 1994; Siegel, 1994; Hulme & Roodenrys, 1995), as noted in **Chapter 2**.

Early phonological processing skills also predicted later reading ability in the present sample of incipient readers although the three conditions of the phonological oddity task were found to display differential predictive abilities at different stages of development. The ability of the pre-reader to differentiate between words on the basis of their medial sounds, for example, proved able to predict reading ability at each stage of testing, whereas the other components of phonological processing ability did not emerge until later. This is widely reported in the literature (Maclean *et al*, 1987; Ellis & Large, 1987; Bryant *et al*, 1989)

Surprisingly, performance in the last-sound-different condition of the task failed to predict subsequent reading ability although it did correlate with concurrent literacy skills at the final testing stage. This is surprising in that it is tapping essentially the same skill (rhyme awareness) as the middle-sound-different condition. Alliterative awareness only emerged later (from stage 3) to predict subsequent reading ability in children who had already acquired some elementary reading skills (see also Bradley, 1980; Goswami, 1986). As discussed in **Chapter 2**, the ability to focus on the initial sounds of words requires a more explicit phonological awareness than that needed for the performance of the rhyming conditions of the oddity task. It is suggested, therefore, that alliterative awareness is not a pre-cursor to reading but that early reading instruction brings with it the palpable realisation that words are composed of units of sound (represented in the written form by letter clusters) which may be manipulated to facilitate future reading development.

The two measures of visual perception - the block design task and the matching of letter-like forms task - were also found to predict reading ability differentially at different stages of the study. Whereas the children's performance of the block design task at stages two and three predicted the emergence of their earliest reading skills at stage three, this measure failed to emerge again as a significant predictor throughout the course of the study. Performance on the matching of letter-like forms task, however, showed a different pattern and emerged as the more far-reaching predictor of reading ability. Children's ability on this task between the ages of 3 1/2 to 4 1/2 years (stages 1 to 3) was found to predict reading ability up to and including the final measure taken at the age of 5 1/2 years. It is suggested that some basic degree of visual ability, as indexed by the block design task, is necessary for the initial acquisition of literacy skills; the influence of this fundamental ability is subsequently replaced by a more sophisticated aspect of visual processing, reflected in the performance of the matching of letter-like forms task. To perform this task the children are required to focus on, and discriminate between, letter-like shapes, employing similar processes to those used in the identification of letters during reading (Gibson, 1969). Early ability on this task would enhance the efficacy of elementary reading instruction (Van de Voort & Senf, 1973; Spreen & Haaf, 1986; Feagans & Merriwether, 1990). Conversely, elementary reading instruction provides the children with greater exposure to such visual forms which would again feed into the relationship between competence on the matching of letter-like forms task and reading ability (Kavale, 1982; Hatchette & Evans, 1983).

Unsurprisingly, reading ability at each stage of the investigation significantly predicted subsequent reading ability in a demonstration of the "Matthew effect" (Stanovich, 1986). This effect, analogised from the Parable of the Talents related in the Gospel according to St Matthew, is such that achievement follows a cumulative path: "For unto everyone that hath shall be given, and he shall have abundance, but from him that hath not shall be taken away even that which he hath" (XXV: 29). Children who acquire early reading skills with ease will therefore continue to develop their reading skills at a faster rate than that demonstrated by children who experience early difficulty.

6.6.3 How do these relationships change over time?

6.6.3 (a) Handedness and the early reader

In contrast to previous reports linking lateralised electrophysiological or behavioural measures to the emergence of the neuropsychological context in which reading develops (see, for example, Rippon, 1991; Wood *et al*, 1991; Galaburda *et al*, 1994) the present study generally failed to reveal any such relationship. Handedness in the pre-literate child (at stage 2) was found, however, to directly predict reading ability at stage 3; this relationship between the two measures was negative such that better right than left hand skill (as indicated by negative laterality indices) was associated with better reading ability at the first stage of testing at which this was apparent.

The failure to find any apparent relationship between cerebral lateralisation and the development of the cognitive measures which support reading acquisition may be explained in terms of the reliance of this investigation on handedness as the sole (indirect) index of lateralisation. Evidence would indicate, for example, that whereas handedness measures may reflect different *degrees* of lateralisation, the extent to which they reflect inter-hemispheric differences in *direction* of lateralisation is equivocal (see Peters, 1995 and Beaton, 1995 - submitted for publication - for comprehensive reviews of research investigating the relationship between handedness and cerebral asymmetries). Any cognitive differences between individuals at disparate points along the handedness continuum will be difficult to interpret in terms of differential hemispheric lateralisation (Porac & Coren, 1981; Bryden & Saxby, 1986). Future attempts to investigate the relationship between hemispheric organisation and the development of the linguistic and visual abilities necessary to support the acquisition of literacy skills should, therefore, involve the application of more direct measures of lateralisation than revealed by the individual's handedness.

As has already been discussed, the present study found significant relationships between the different cognitive measures and reading ability over subsequent testing stages. The results of the partialled time-lag correlations expanded on these earlier findings and revealed that not only do these relationships continue to emerge when reading ability at each stage is stringently controlled for, but furthermore, they revealed the direction of the relationship at each stage. These relationships are discussed below.

6.6.3 (b) Cognitive context and reading development: Phonological awareness

Once again the sub-types of phonological awareness were found to be related differentially to reading ability across the course of the investigation. With the outcome reading ability at each stage removed from the equation all three measures of phonological awareness in the pre-literate child significantly predicted the emergence of early reading skills. Once these early reading skills had been acquired, however, rhyme awareness (as indexed by the middle- and last-sound-different conditions) ceased to causally predict subsequent reading ability. Alliterative awareness continued to exert its influence until the end of the first year of formal reading instruction. By this stage most of the children will have mastered the basic grapheme-phoneme conversion skills necessary for reading and will have built up a fairly substantial sight vocabulary (Barron, 1986; Reitsma, 1990; Adams, 1990). The need to focus on the individual sounds of words will be diminishing in favour of more automatic whole-word recognition (Backman, Bruck, Hebert & Seidenberg, 1984; Ehri, 1985; Ehri & Wilce, 1985).

The present findings support previous reports of reciprocal causality between phonological awareness and reading development (Stanovich *et al*, 1984; Perfetti *et al*, 1987; see also Share, 1995 for a review), as reading ability is found to be significantly related to phonological awareness across each adjacent stage of the study. Although the evidence attests to the primacy of phonological awareness at the outset of this relationship (Bradley & Bryant, 1983; Share *et al*, 1984; Mann, 1991) the acquisition of early literacy skills, undoubtedly, also serves to promote subsequent phonological awareness by providing the individual with an insight into the phonemic principles which underlie the alphabetic orthography.

6.6.3 (c) Cognitive context and reading development: Phonological memory

Even controlling for previous reading ability, memory span was again found to exert a significant causal influence over the development of reading skills at each adjacent stage. As noted above, novice readers learn to identify vast numbers of words over the early stages of reading development. Children rapidly build up a sight vocabulary of words with which they most frequently come into written contact, and it is suggested that by the fifth year of schooling children encounter approximately 10,000 new words each year (Nagy & Herman, 1987). It is hardly surprising, therefore, that memory capacity is able to predict the development of an individual's reading capability.

Although reading at stage 3 was also found to exert some reciprocal influence over memory capacity at stage 4 this relationship was not sustained over the ensuing stage of testing. It is possible that this early effect reflects the children's increasing phonological skills, such that early reading development may enhance phonological memory skills indirectly by ameliorating the phonological encoding of to-be-remembered information. This influence is relatively short-lived.

6.6.3 (d) Cognitive context and reading development: Visual perception

Contrary to the far-reaching influence of visual skills revealed by the earlier multiple regressions, once reading ability was controlled for at each stage of testing the actual influence of visual ability appeared to be fairly minimal. The pre-literate children's performance on the block design and the matching of letter-like forms tasks significantly predicted the emergence of reading skills at stage 3 but not beyond. Thus, it would appear that some ability to focus on the visual forms of letters is important for the early acquisition of reading (Adelman & Taylor, 1986; Feagans & Merriwether, 1990). This would coincide with the discrimination net guessing stage of Marsh *et al*'s (1981) Cognitive Developmental model and the corresponding logographic stage of Frith's (1985) Three Stage model of reading development (see **Chapter 2**). Once formal (phonics) reading instruction commences, however, the influence of visual skills is superseded by that of phonological processing ability.

6.7 Conclusion:

On the basis of the preceding discussion it may be concluded that phonological abilities, as indexed by measures of alliterative awareness, rhyme awareness and phonological memory capacity, are vital to the development of competent reading skills. Furthermore, these abilities appear to not only facilitate the acquisition of literacy, but they are also themselves enhanced by increasing reading skills. Support is offered to suggestions that reading and phonological abilities develop in a mutually enhancing relationship. Visual processing skills were also found to predict reading ability in the early stages of literacy development, possibly corresponding to the visual/ logographic stages espoused by the stage models of reading development (Marsh *et al*, 1981; Frith, 1985). These are discussed in **Section 2.2**.

The present study is also able to offer some support for the use of objective measures of handedness as indirect indices of cerebral lateralisation. The shift towards greater dextrality (hand skill and hand preference) between the second and third stages of the investigation, coinciding with the commencement of formal reading instruction, may be interpreted as reflecting some sort of increase in cortical maturation of the left hemisphere at this stage of development. The precise nature of this relationship is unclear on the basis of the present findings. The cross-sectional studies reported in **Chapters 7** and **8** employ more sophisticated indices of cerebral lateralisation in children in whom the development of literacy is fairly well established, and in children in whom this process has failed to develop as expected. Hopefully these investigations will help to clarify this issue.

Having investigated the relationship between emerging literacy skills and the cognitive profiles of normal children in the earliest stages of reading acquisition it would be instructive to extend this investigation to assess the relationship between these same variables in children with divergent literacy skills. This is the rationale for performing the studies detailed in the next chapter. In addition to employing the cognitive test battery and the indirect measures of cerebral lateralisation (hand preference and hand skill) used in the present study, the next study is to employ more direct measures of cerebral lateralisation. Thus, as noted above, the aim is to further elucidate the relationship between literacy skills and the cognitive neuropsychological profiles of children at different points along the reading ability continuum.

~ CHAPTER 7 ~

Cross-sectional (N100/ P200) study: Lateralisation and cognitive ability as a function of reading skill

7.1 Introduction:

In view of the difficulties in defining exactly what constitutes dyslexia (as discussed in **Section 3.1**), the present study adheres to the general assumption that the term 'developmental dyslexic' applies to children whose failure to acquire reading skills commensurate with their general intellectual ability may not be explained by lack of educational or socio-cultural opportunity, or by any overt neurological disorder.

7.1.1 Cognitive deficits and dyslexia

Since the earliest attempts to delineate the problems experienced by children who have difficulty in learning to read, a considerable body of evidence has amassed associating dyslexia with poor performance on numerous cognitive tasks requiring the ability to process sounds and visual images. While early literacy theorists focused almost exclusively on the importance of visual processing skills to reading, the emphasis has shifted somewhat over the last decade to highlight the primary role of phonological awareness in the acquisition of literacy (see **Section 2.3**), and of phonological processing impairments in developmental dyslexia (**Section 3.2**).

In terms of literacy development the primary consequences of a reduction in the ability to process the sounds of words are twofold. Not only will such a reduction impair a child's capacity to "sound out" letter strings and to draw analogies between words with similar sounds to aid in the reading of unfamiliar words, at a more fundamental level it will impair a child's competence to associate printed letters with their spoken representations.

This latter consequence highlights the particular importance of phonological processing skills to reading via their involvement in phonological memory. Memory capacity has been considered as another possible source of variation between good and poor readers, and its bearing on developmental dyslexia should not be over-looked (Bryant & Bradley, 1985; Johnston *et al*, 1987).

Visual processing skills have also been found to differentiate between competent and inferior readers (Feagans & Merriwether, 1990; Goulandris & Snowling, 1991; Livingstone *et al*, 1991) although the exact nature and extent of between-group differences is unclear (see **Section 3.4**). The present study included measures of visual processing skills in the hope that any fundamental differences in ability between the good and impaired readers would emerge.

7.1.2 Neuropsychological anomalies and dyslexia

Neuropsychological studies undertaken to investigate the subcortical correlates of reading impairments frequently link developmental dyslexia with reduced or delayed left hemisphere specialisation for the processing of language (Schachter *et al*, 1987; Larsen *et al*, 1990. See **Chapter 4**). Such studies generally employ one of three measures of lateralisation: simple tests of handedness, dichotic listening tasks or the measurement of auditory evoked potentials (AEPs). These measures represent the three levels of Frith's (1995) theoretical framework (see **Section 4.5**) and all three are employed in the present study in an attempt to determine whether differential patterns of brain lateralisation may discriminate between good and poor readers.

7.1.2 (a) Neuropsychological anomalies and dyslexia I: as indexed by handedness

The left cerebral hemisphere is responsible for the mediation of language processes in the majority of people (Porac & Coren, 1981; Kolb & Whishaw, 1990). If hypotheses linking developmental dyslexia with some form of anomalous cerebral lateralisation are correct, it may be expected that this would be reflected in the dyslexic's handedness (see **Section 4.4.1.**).

The elucidation of the relationship between handedness and reading ability is due largely to the work of Annett and colleagues (Annett & Kilshaw, 1984; Annett, 1985; Annett & Manning, 1990b). These researchers have demonstrated that whereas individuals falling towards both extremes of the hand skill distribution are at risk of poor reading development, the cognitive impairments associated with these reading difficulties differ for children at each extreme (Annett & Manning, 1990b; Annett, 1992b). Children towards the left of the distribution, for example, are also likely to experience difficulties with phonological processing (Annett & Manning, 1990b; Annett, 1992b) while those at the right of the distribution stand a greater risk of experiencing impaired visuospatial abilities (Annett & Kilshaw, 1984; Annett & Manning, 1990a, b). Recent studies investigating hand skill in samples of dyslexic children with particularly poor phonological processing skills have supported these earlier findings (Brunswick & Rippon, 1993; Rippon & Brunswick, 1994).

Although empirical evidence appears to support suggestions of a relationship between handedness, left hemisphere processing skills and reading ability in good and poor readers, the precise nature of this relationship needs to be quantified (see also **Chapter 6** for a discussion of this relationship in novice readers).

7.1.2 (b) Neuropsychological anomalies and dyslexia II: as indexed by dichotic listening

Whereas a simple measure of hand skill offers an indication of the "structural dominance" of each of the two cerebral hemispheres, a slightly more direct index of the relative participation of each hemisphere in the processing of language is provided by the dichotic listening task (see **Section 4.4.2.**). According to the theoretical underpinnings of this paradigm, normal readers, with left hemisphere language representations and a verbal perceptual bias to the right side of space, will display a right ear advantage for the processing of verbal stimuli regardless of the specified ear of report (Murray *et al*, 1988; Boliek *et al*, 1988; Bloch & Hellige, 1989).

If theories of abnormal lateralisation in reading impaired children are correct, it would be expected that these children would show either a substantially reduced right ear advantage or they may fail to show any particular ear advantage for the processing of verbal stimuli. Theoretically, therefore, this paradigm should discriminate between dyslexics and normal readers. In reality the evidence is not so clear. Dyslexic children have variously been reported to display verbal REAs comparable to those of normal readers (Obrzut *et al*, 1981; Kershner, 1985) or no REA (Hynd *et al*, 1979; Obrzut *et al*, 1985) under conditions of free-recall and forced right ear recall. When asked to recall stimuli perceived at the left ear dyslexics have been found to display either an attenuated REA or an LEA (Boliek *et al*, 1988; Kershner & Micallef, 1992; Obrzut *et al*, 1992). The implications of these results have been discussed in **Chapter 4**.

As noted in **Section 4.4.3**, while dichotic listening may be useful for highlighting individual differences in the direction of inter-hemispheric lateralisation, its utility for revealing more subtle differences in degree of inter- and intra-hemispheric lateralisation is questionable (Harshman, 1988; Ahonniska *et al*, 1993). Researchers interested in these more subtle differences are increasingly employing behavioural measures in combination with electrophysiological measures, specifically the auditory-evoked potential (AEP).

7.1.2 (c) Neuropsychological anomalies and dyslexia III: as indexed by AEPs

In spite of the obvious need to validate behavioural measures of cerebral lateralisation, and to expand on the information provided by these measures, a relative dearth of studies employing both dichotic and electroencephalographic techniques exists in the literature. The evidence that is available, however, is generally encouraging. The majority of these studies report finding significantly larger amplitude and earlier latency AEPs (specifically the N100 and P200 components) in the left hemisphere than in the right during the processing of dichotically presented verbal stimuli (van de Vijver *et al*, 1984; Woods, Hillyard & Hansen, 1984; see **Section 4.4.5**). Right ear advantages on the verbal dichotic listening task also point towards a left hemisphere dominance for the processing of these stimuli, and Van de Vijver *et al's* (1984) observation that the greatest ERP asymmetry occurred immediately preceding recall (during the rehearsal period) has been interpreted as showing a greater "mobilization of resources" in the left hemisphere during this stage of processing.

The combination of behavioural and electrophysiological measures of cerebral lateralisation has obvious implications for an investigation into the psychophysiology of literacy development in children with and without reading impairments. To date, however, no study recording AEPs in normal and dyslexic children during the processing of verbal dichotic stimuli exist in the literature, although a small number of studies have combined simple behavioural tasks and electrophysiological measures (visual evoked potentials and EEG) in children of different reading abilities.

These studies indicate that normal readers display ERP correlates (larger amplitudes and earlier latencies) indicating the expected pattern of left hemisphere dominance for the processing of verbal stimuli and right hemisphere dominance for the processing of non-verbal stimuli. Dyslexic children either show no such distinction or an apparent reversal of lateralisation (Landwehrmeyer *et al*, 1990; Segalowitz *et al*, 1992). Whether these findings indicate an inability in the dyslexic children to selectively attend to the stimuli and to apply the appropriate processing strategy to the behavioural task, or whether the distinction between the two groups of readers exists at a more fundamental, physiological, level remains to be determined (see **Section 4.4.2 (b)** for a discussion).

Of particular interest to the present study are the early components of the ERP: the N100 and the P200 (see **Section 4.4.5** for an outline of the rationale behind the selection of these particular components). Occurring within the first 200 milliseconds post stimulus presentation these components are thought to reflect sensory/ attentional factors prior to cognitive processing (Hillyard & Picton, 1979; Naatanen & Picton, 1987). It has been suggested that in order to detect differences in perceptual abilities between good and impaired readers it is necessary to employ a demanding behavioural task (Goetzinger, Dirks & Baer, 1960). In the present study it is hoped, therefore, that any between-group dichotic ear effects which result from differences in the perception of information received via contra- and ipsi-lateral auditory pathways (see **Section 4.4.2 (a)**) might be elucidated by recording ERPs contemporaneous with the presentation of dichotic stimuli.

7.1.3. The rationale of the present study

Evidence is amassing which points to the comprehensive influence of phonological processing skills on literacy development and to the relationship between phonological deficits (including their contribution to phonological memory impairments) and developmental dyslexia. Visual processing difficulties have also been included amongst the "fundamental cognitive disabilities" which appear to underlie dyslexia. Neuropsychological evidence has implicated abnormal cerebral lateralisation in dyslexia, such that a reduction in the normal left hemisphere superiority for the processing of linguistic stimuli may be a key constitutional factor in the impairment of verbal processing. Such evidence is derived from indirect measures of lateralisation, such as handedness, and also from more direct measures, including the dichotic listening paradigm and the recording of AEPs.

The current investigation was undertaken to examine the cortical functional organisation of children with established, but divergent, reading capabilities, and to determine the extent to which this organisation may be indexed by measures of handedness, dichotic listening and auditory evoked potentials. A further aim was to expand on the findings from the longitudinal study (reported in **Chapter 6**) by investigating the cognitive correlates of reading in competent and impaired readers. The present study employed all of the measures administered in the longitudinal study, in addition to the dichotic listening task with contemporaneous recording of event-related potentials (see **Sections 5.2.** and **5.3.** for a justification of the selection of these measures). The intention was to shed some light on the cognitive and neuropsychological profiles of dyslexia.

STUDY1:

7.2. Method:

7.2.1. Subjects:

A sample of 36 children, whose ages ranged between 7:07 and 11:07 years (mean age = 9:01 years ± 1.15) participated in this study. Of these, 18 children were developmentally dyslexic and 18, without any apparent reading impairments, acted as chronological-age matched controls.

The dyslexic children were recruited via the Specific Learning Difficulties Support Service. All had previously been tested by an educational psychologist and identified as developmentally dyslexic. British Picture Vocabulary Scale scores for the sample yielded a mean of 99.92 (± 3.71). The control subjects were recruited via a newspaper advertisement calling for subjects to participate in a reading research project.

The dyslexics (15 boys and 3 girls) had ages ranging between 7:07 and 11:07 years (with a mean age of 8:96 years ± 1.36). They showed a mean discrepancy of 2:1 years (± 1.21 years) between chronological-age and reading-age on the British Ability Scales Word Reading test. Within this sample 15 of the children were right handed and 3 were left handed by self-report. This was confirmed by the Annett Hand Preference Questionnaire (Annett, 1970); hand preference ratings ranged from 1 to 8 (mean rating = 3.06 ± 2.34).

The 18 chronological-age matched normal readers (8 boys, 10 girls) ranged in age from 8:0 years to 10:11 years (with a mean chronological-age of 9:05 years ± 0.92). All were right-handed according to self-report and hand preference ratings on the Annett Hand Preference Questionnaire (Annett, 1970) which ranged between 1 and 3 (with a mean rating of 1.61 ± 0.92). These ratings indicate that the sample consisted of a combination of pure right-handers and right-handers with weak to mild left-hand tendencies. All of these children were reported by their parents to be performing at an appropriate level for their age in school. The mean reading-age of the sample was 11.07 years (± 1.50).

All children spoke English as a first language and discussions with the parents revealed that none of the children had a history of any neurological, psychiatric or hearing disorders.

The imbalance in the sex of the subjects within each sample is acknowledged. This was unavoidable. The dyslexic sample consisted of all of the children referred by the Specific Learning Difficulties Support Service while the control sample consisted of all of the respondents to the newspaper advertisement. As no intention existed in the present study to investigate the cognitive and literacy skills of children as they relate to sex, however, this was considered to be acceptable although sex was entered as a covariate in all analyses to control for any possible influence it may exert over the results.

7.2.2 Stimuli and Apparatus:

7.2.2 (a) Indirect measures of cerebral lateralisation (hand preference and skill):

The Annett (1970) hand preference questionnaire was used to determine hand preferences for undertaking various skilled unimanual activities. In order to verify the children's hand preference responses the objects in question were available for the children to use (see **Chapter 5**). To supplement the information obtained from the hand preference questionnaire an Annett (1970) pegboard was used to assess left and right hand skill (administered as described in **Chapter 5**). This pegboard was placed on a table of such a height as to enable the children to perform the task whilst standing.

7.2.2 (b) Neuropsychological measures:

The children's cognitive processing abilities were assessed using a battery of tests taken from the British Ability Scales (Elliott *et al*, 1983). These were the same tests as administered in the longitudinal study - the recall of digits task, the matching of letter-like forms test and the block design (level) test. The children's reading ability was assessed using the word reading test from the Scales. Bradley & Bryant's (1983) phonological oddity task was again administered to quantify the children's phonological processing skills.

7.2.2 (c) Direct measures of cerebral lateralisation:

The dichotic listening test involved the presentation of 3 blocks each of 32 pairs of consonant-vowel syllables (/ba/, /da/, /ga/, /ta/, /pa/, /ka/) for free-recall, forced left ear recall and forced right ear recall (see Hugdahl & Andersson, 1986), as per the paradigm described in **Section 5.3.2**.

7.2.2 (d) Electroencephalographic measures:

ERPs were recorded from the whole of the scalp area and from the linked ear reference electrodes during the administration of the dichotic listening task, as described in the methodology chapter (**Section 5.4.**).

7.3 Procedure:

Children were brought individually to the university by their parents who remained present throughout the testing session, although out of sight of the child. Prior to the start of testing proper the procedure was outlined to the child and the parents, any questions concerning the exact nature of the tests were answered, and informed parental consent obtained. The children were also reassured that the tests were designed for children of different ages and abilities, so that while some would cause no problems at all, others may be too difficult. If at any time the child felt unable to solve a particular puzzle, they were to tell the experimenter so that they could progress to the next stage of testing.

The testing session was divided into four sections: (1) the administration of the psychometric tests and the hand preference questionnaire which lasted approximately 20 minutes; (2) a brief respite for the child whilst they sat watching cartoons, during which time the electrode cap was fitted; (3) the dichotic listening task with contemporaneous recording of auditory evoked potentials, and (4) the completion of the pegboard task. The entire testing session lasted approximately an hour.

7.3.1. Psychometric testing and assessment of hand preference:

Testing was carried out in a sound-attenuated cubicle within the psychophysiology laboratory at the University of Warwick. During the initial stage of the testing session the child was sat in a comfortable chair facing the experimenter. The psychometric tests were presented in a random order, on a table at a comfortable height for the child. These tests included the recall of digits task, the matching of letter-like forms task, the block design task, the phonological oddity task and the word reading test. The hand preference questionnaire was also completed at this stage (see **Chapter 5**).

7.3.2. AEP/ Dichotic listening task:

Having completed the first stage of testing the child was led from the testing cubicle into the main body of the psychophysiology laboratory to be fitted with the electrode cap, as detailed in **Section 5.4.1**. Following this procedure the child was led back to the testing cubicle and the dichotic listening task was administered as described in **Chapter 5** (see also Hugdahl, 1988). Auditory-evoked potentials were recorded during the child's performance of the dichotic listening test; these were averaged on-line to produce single waveforms for each electrode within each dichotic listening condition.

7.3.3. Pegboard task:

Following completion of the dichotic listening task subjects were again led out of the testing cubicle for the removal of the electrode cap and to perform the pegboard task (as described in **Chapter 5**; see Annett, 1985).

The children and their parents were subsequently debriefed and any questions were answered. The child was given a £5.00 gift voucher and a topographical brain map.

7.4. Data reduction:

Prior to statistical analysis the psychometric tests, the handedness measures and the dichotic listening task were marked in accordance with their scoring instructions (see **Section 5.5**).

In quantifying the electroencephalographic measures, the amplitudes and latencies of two AEP components - the N100 and the P200 - were measured. Measuring bias was avoided by employing strict criterion to identify the components. The N100 was designated as the largest negative peak between 50 and 150 msec after stimulus onset and the P200 as the largest positive peak between 170 and 250 msec after stimulus onset (see Naatanen & Picton, 1987; Segalowitz *et al*, 1992).

The goal of the present study was the identification of cognitive and electrophysiological correlates of reading competence in children distributed along the reading ability continuum. As mentioned in **Section 7.2.1**, no intention existed to investigate the potential influence of sex on reading ability although its possible influence cannot be ignored; therefore, sex was entered as a covariate in all analyses.

Statistical analysis of the indirect laterality measures and of the results from the psychometric test battery involved the calculation of Analyses of Variance (ANOVAs) with reading ability group entered as the between-subjects factor. Repeated measures on the dependent variables were entered into the ANOVAs where necessary in the investigation of within-subject effects.

The electrophysiological data (ERP amplitudes and latencies) were analysed separately for the N100 and P200 components. These analyses took two forms. In the first analyses ANOVAs were calculated with one between-subjects factor (reading ability group) and two within-subjects factors: cortical region (11 levels: F3, Fz, F4, C3, Cz, C4, P3, Pz, P4, T5, T6) and dichotic listening recall condition (3 levels: free recall, forced right ear recall, forced left ear recall). The second series of analyses were 2 (hemisphere) x 3 (dichotic listening recall condition) multivariate ANOVAs with reading ability group as the between-subjects factor. These secondary analyses were carried out to provide an indication of possible between-group differences in scalp topography of the waveform components, and thus to complement the results from the initial wave of analyses. In reporting the results of these analyses main within-subject effects (i.e. cortical region, dichotic listening recall condition or hemisphere) will not be presented except where they interact with reading ability group.

Although the ANOVA is widely regarded as a robust technique in the computation of inferential statistics it may be argued that the model brings with it an inherent incongruity with regards to the analysis of ERP data (Glaser & Ruchkin, 1976; McCarthy & Wood, 1985). A significant ANOVA interaction between variables A and B, for example, would be conventionally interpreted as reflecting differences in variable A across each of the levels of B. To relate this to ERP data, it may be inferred that a significant cortical region by task condition interaction is demonstrating different patterns of activation across the scalp electrodes in different experimental conditions. This conclusion may be specious, however. Changes in the amplitude of the electrical signal recorded by scalp electrodes are multiplicative: a 2-fold increase in the strength of the signal is represented across each location on the scalp. This is incompatible with the additive nature of the ANOVA which would assume that such an increase would add a constant amplitude to the level of activity at each recording site. It is possible, therefore, that significant cortical region by condition (or group) interactions may reflect nothing more than a change in underlying source strength. One solution to this problem is to scale the amplitudes prior to the computation of the ANOVAs. Significant interactions may be safely interpreted, therefore, as reflecting genuine differences in scalp topography rather than artifactual differences in amplitude between conditions or subject groups.

In the present study data which yielded significant interactions between cortical regions/ hemispheres and experimental conditions/ groups were corrected to equate amplitude across conditions (and subjects). This procedure involved the equation:

$$\text{ERP component } (i') = \frac{[\text{ERP component (i) - ERP component (min)}]}{[\text{ERP component (max) - ERP component (min)}]}$$

where i is a given electrode; *i'* is the normalised amplitude; min is the minimum within-group mean value across the electrode sites and max is the maximum within-group mean value across the electrodes (see McCarthy & Wood, 1985; Duncan *et al*, 1994; Rugg, Doyle & Wells, 1995). These normalised data were re-analysed.

Pearson Product Moment correlation coefficients were calculated to investigate the strength of the relationship between the behavioural and electrophysiological measures taken concurrently during the dichotic listening task. The N100 and P200 AEP measures were averaged over the left and right hemispheres and difference scores were calculated between each lateral pair of electrodes (right hemisphere - left hemisphere) to provide measures of physiological asymmetries in each hemisphere (see Tenke, Bruder, Towey, Leite & Sidtis, 1993). These measures were correlated with the left and right ear accuracy scores and ear advantage indices from the dichotic listening test.

Significance levels for all analyses were adjusted with the Greenhouse-Geisser procedure (Greenhouse & Geisser, 1959) to correct for non-sphericity; Tukey's Honestly Significant Differences (HSD) test was used as a post-hoc investigation of significant results. To circumvent the potential statistical dangers inherent in the performance of multiple Tukey tests within a single series of pairwise contrasts (an increased risk of Type 1 errors), the results of these tests were not considered significant unless the probabilities proved less than 0.05 divided by the number of contrasts (i.e. 2 pairwise contrasts would demand the adoption of a significance level of 0.025).

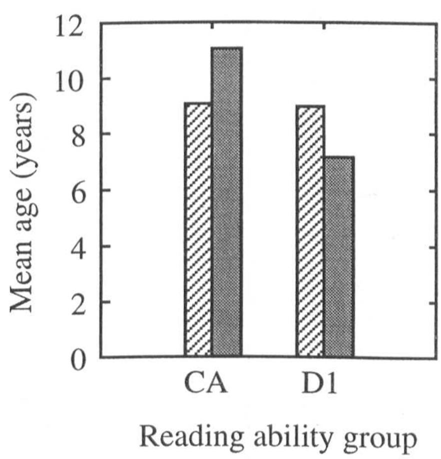
7.5. Results:

The results of this study are to be considered in two main sections. Firstly the indirect laterality measures - hand preference and skill - and the psychometric tests; secondly the direct laterality measures - the dichotic listening task and the auditory evoked potentials. A third section will report the results of analyses investigating the degree of correlation between behavioural measures (phonological oddity task and dichotic listening task performance) and neuropsychological indices (handedness and ERP).

7.5.1. Sample characteristics

Analysis of the children's chronological and reading-ages (displayed in **table 7.1** and illustrated in **figure 7.1**) revealed that, as expected, the dyslexic sample differed significantly from the chronological-age matched sample on reading-age [$F(1, 33) = 29.56$; $p < 0.005$] but not chronological-age ($p = 0.72$).

Figure 7.1. Mean chronological-ages and reading-ages of the normal and impaired readers



Key:

Reading-age   Chronological-age

CA = chronological-age matched good readers; D1 = dyslexic readers

Table 7.1. Mean ages and handedness measures (with standard errors).

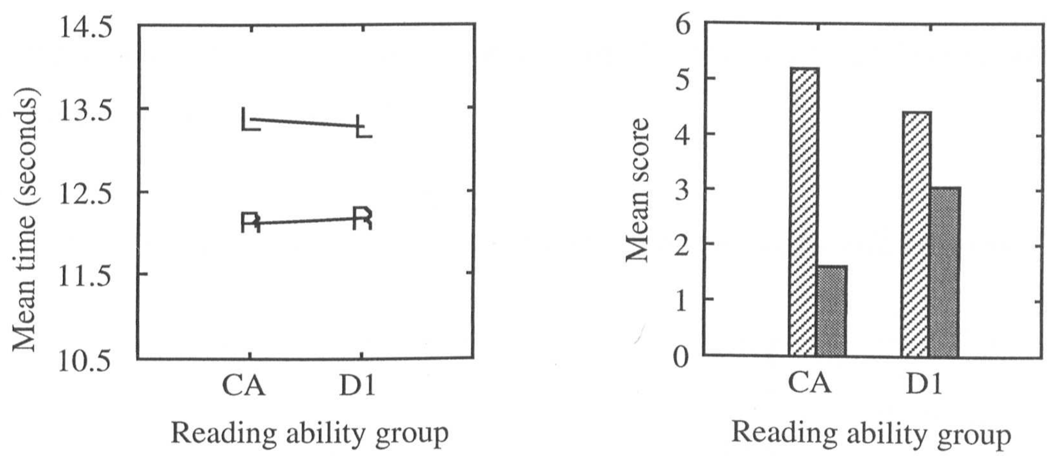
Reading group	**Chronological-age: years**	**Reading-age: years**	**Peg Left: seconds**	**Peg Right: seconds**	**Pegboard Laterality Indices**	**Hand Preferences**
Chronological- age controls	9.05 (±0.22)	11.07 (±0.35)	13.39 (±0.32)	12.13 (±0.42)	5.17 (±1.10)	1.61 (±0.22)
Dyslexic readers	8.96 (±0.32)	7.12 (±0.22)	13.29 (±0.38)	12.17 (±0.38)	4.42 (±1.18)	3.06 (±0.55)

Key: Reading-age = as determined by the British Ability Scales Word Reading test; Peg Left = left hand mean completion time on the pegboard; Peg Right = right hand mean completion time on the pegboard; Pegboard Laterality Indices = ((peg left-peg right)/(peg left+pegright)) * 100; Hand Preferences = score on the Annett Hand Preference questionnaire.

7.5.2 Indirect Laterality measures

Within- and between-group comparisons of the children's hand skill characteristics (see **table 7.1**) revealed that within each group the right hand times were faster than those of the left [CA controls [F (1, 17) = 20.33; p < 0.005]; Dyslexics 1 [F (1, 17) = 12.02; p < 0.005]; this is seen in **figure 7.2**.

Figures 7.2 and 7.3. Handedness characteristics of the good and impaired readers: mean hand skill and hand preference measures



Key: Pegboard completion times: R = Right hand; L = Left hand
Hand preference Laterality indices

CA = chronological-age matched good readers; D1 = dyslexic readers

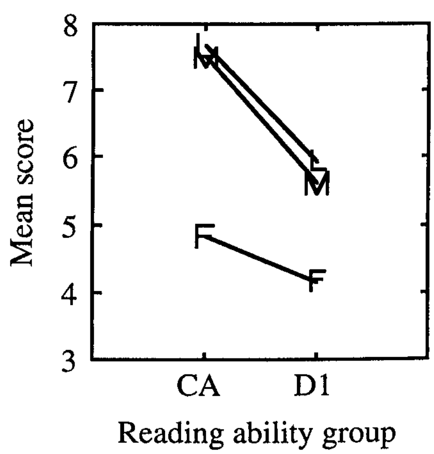
No differences were found in either left (p = 0.46) or right (p = 0.70) hand pegboard completion times or in the hand skill laterality indices (p = 0.70) between the two groups of children. The two did prove significantly different in terms of hand preference, however [F (1, 33) = 4.04; p = 0.05]. This finding, illustrated in **figure 7.3**, reflects the higher mean hand preference value of the dyslexic children compared with the matched control sample. This indicates a lesser influence of the right hand in the performance of the skilled unimanual activities by the dyslexics than that by the control children, i.e. the dyslexics may be categorised as displaying "mixed" handedness.

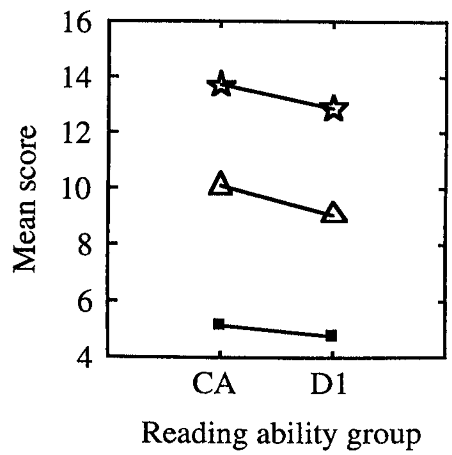
7.5.3 Psychometric measures

The data from the phonological oddity task (see **table 7.2**) were analysed in two ways. Firstly collapsed across reading groups to examine differences between the three phonological conditions, and secondly by comparing scores in the three conditions between the reading ability groups.

Overall the results showed that the children performed significantly better in both the last-sound-different [$F(1, 35) = 40.44$; $p < 0.005$] and the middle-sound-different [$F(1, 35) = 30.97$; $p < 0.005$] conditions than in the first-sound-different condition (illustrated in **figure 7.4**). No difference in accuracy emerged between the middle- and last-sound-different conditions ($p = 0.11$).

Figures 7.4 and 7.5. Psychometric test performance according to reading group.





Key: Phonological oddity task: F = First-sound-different; M = Middle-sound-different; L = Last-sound-different condition mean scores

✰ Letter-like forms Δ Block design ■ Digit span

CA = chronological-age matched good readers; D1 = dyslexic readers

Table 7.2. Mean scores (with standard errors) on the psychometric tests achieved by the chronological-age control and dyslexic children.

Reading group	First-sound-different	Middle-sound-different	Last-sound-different	Digit span	Block design	Matching of letter-like forms
Chronological-age controls	4.83 (±0.57)	7.50 (±0.23)	7.67 (±0.16)	5.17 (±0.82)	10.06 (±0.84)	13.72 (±0.41)
Dyslexic readers	4.17 (±0.38)	5.61 (±0.42)	5.94 (±0.40)	4.80 (±0.71)	9.06 (±0.82)	12.87 (±0.65)

Key: First-sound-different = Bryant & Bradley first-sound-different condition; Middle-sound-different = Bryant & Bradley middle-sound-different condition; Last-sound-different = Bryant & Bradley last-sound-different condition.

A comparison of the data obtained from the two groups of children showed that the control readers performed with significantly greater accuracy than the dyslexic children in the last-sound-different condition [$F (1, 33) = 13.37$; $p < 0.005$] and in the middle-sound-different condition [$F (1, 33) = 10.49$; $p < 0.005$], but not in the first-sound-different condition ($p = 0.65$).

No significant differences between the matched good and poor readers emerged from statistical analysis of the data obtained from the remaining psychometric measures (see **table 7.2** and also **figure 7.5**) although the control readers tended to out-perform the dyslexic children.

7.5.4 Direct Laterality Measures I: dichotic listening

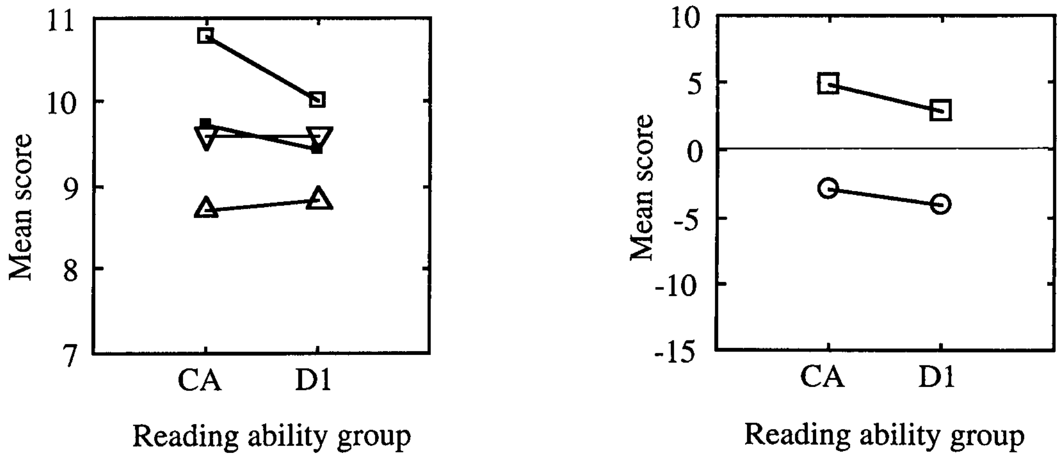
Performance in the three recall conditions of the dichotic listening task also failed to differentiate significantly between the good and poor readers (see **table 7.3** and **figure 7.6**), and no significant within-group ear effects emerged from analysis of the dichotic laterality indices (displayed in **figure 7.7**).

Table 7.3. Mean number of correct responses and ear advantage indices (plus standard errors) on the dichotic listening task for the chronological-age matched children.

Reading group	Free recall: Left ear	Free recall: Right ear	Forced recall: Left ear	Forced recall: Right ear	Free recall: E.A.I.	Forced recall: E.A.I.
Chronological-age controls	10.78 (± 0.52)	9.72 (±0.43)	8.72 (±0.60)	9.61 (±0.80)	4.79 (±3.16)	-2.96 (±6.79)
Dyslexic readers	10.00 (±0.64)	9.44 (±0.59)	8.83 (±0.51)	9.61 (±0.56)	2.84 (±3.66)	-4.12 (±3.92)

Key: Free recall E.A.I. = Free recall condition ear advantage indices; Forced recall E.A.I. = Forced recall condition ear advantage indices.

Figures 7.6 and 7.7. Mean left and right ear accuracy in the free and forced ear recall conditions of the dichotic listening task and ear advantage indices for each condition



Key:

Mean accuracy: ▽ Forced Right △ Forced Left ■ Free Right ▫ Free Left
Laterality indices: ▫ Free Recall ○ Forced Recall

CA = chronological-age matched good readers; D1 = dyslexic readers

7.5.5. Direct laterality measures II: Auditory -evoked potentials:

7.5.5 (a) N100 amplitude measures:

Mean N100 amplitudes recorded from each of the electrodes during the three dichotic listening response conditions are displayed in **table 7.4a** (see also **figures 7.8** and **7.10**).

7.5.5. (a) i. Raw waveforms:

Amplitudes recorded at each cortical region varied according to reading ability group [F (10, 340) = 4.45; $p < 0.001$]. This interaction was found by post hoc analysis to indicate that the distribution of the N100 in the control children had a left hemisphere focus (F3, C3 and T5 amplitudes were larger than those recorded at C4, P3, P4 and T6; see **figure 7.9**); the midline electrodes produced the largest amplitudes.

In contrast, the dyslexic children's pattern of maximal activation focused more on the right hemisphere fronto-central electrodes (F4 and C4 amplitudes were greater than those recorded from F3, P3, T5, P4, T6; see **figure 7.11**) in addition to the midline electrodes (all p values < 0.025).

Table 7.4a. Mean N100 amplitudes (microvolts) and standard errors for the chronological-age matched children in each recall condition.

Group	Recall	F3	F4	C3	C4	P3	P4	T5	T6	Fz	Cz	Pz
Controls	**Free**	9.04	13.04	10.30	7.02	6.87	7.30	7.55	6.04	15.28	11.42	11.92
		(± 2.00)	(±4.34)	(±1.66)	(±1.49)	(±0.92)	(±1.41)	(±1.20)	(±1.21)	(±3.56)	(±3.09)	(±2.76)
	Forced Right	8.90	9.80	8.07	7.81	6.91	8.70	10.72	8.03	14.19	10.39	12.70
		(±0.99)	(±1.53)	(±1.04)	(±1.32)	(±1.56)	(±1.87)	(±1.22)	(±1.68)	(±1.73)	(±1.75)	(±1.27)
	Forced Left	13.04	12.16	11.85	8.97	6.75	6.96	9.16	6.27	13.17	10.42	12.50
		(±3.08)	(±3.11)	(±1.18)	(±1.81)	(±0.88)	(±1.06)	(±1.22)	(±1.38)	(±2.41)	(±1.48)	(±2.39)
Dyslexics	**Free**	10.09	13.01	9.18	10.64	8.77	8.73	7.54	7.36	12.02	9.91	9.22
		(±1.19)	(±0.89)	(±1.53)	(±1.44)	(±1.08)	(±1.35)	(±1.28)	(±1.01)	(±1.84)	(±1.73)	(±1.32)
	Forced Right	7.91	8.20	8.93	9.45	7.87	7.98	8.04	9.53	8.78	10.01	9.27
		(±1.58)	(±1.60)	(±1.52)	(±1.74)	(±1.12)	(±1.47)	(±1.08)	(±1.35)	(±1.74)	(±1.57)	(±1.53)
	Forced Left	9.61	10.69	11.23	11.41	10.23	7.83	7.58	9.40	12.19	9.66	10.28
		(±1.33)	(±1.63)	(±1.45)	(±1.55)	(±1.44)	(±1.55)	(±1.10)	(±2.26)	(±2.05)	(±1.95)	(±1.36)

Key:
Recall: {Free - Dichotic listening free recall condition
{Forced right - Dichotic listening forced right ear recall condition
{Forced left - Dichotic listening forced left ear recall condition

Figure 7.8. N100 and P200 components of the evoked-potential from a chronological-age matched control reader (averaged over the 3 response conditions)

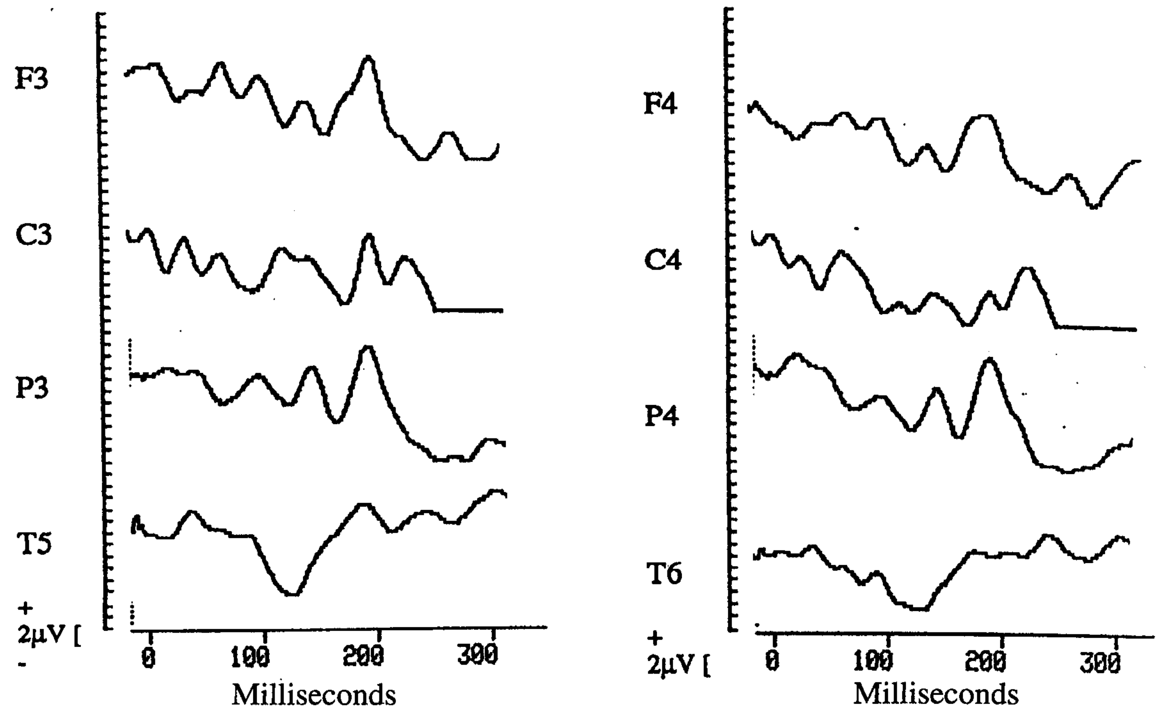
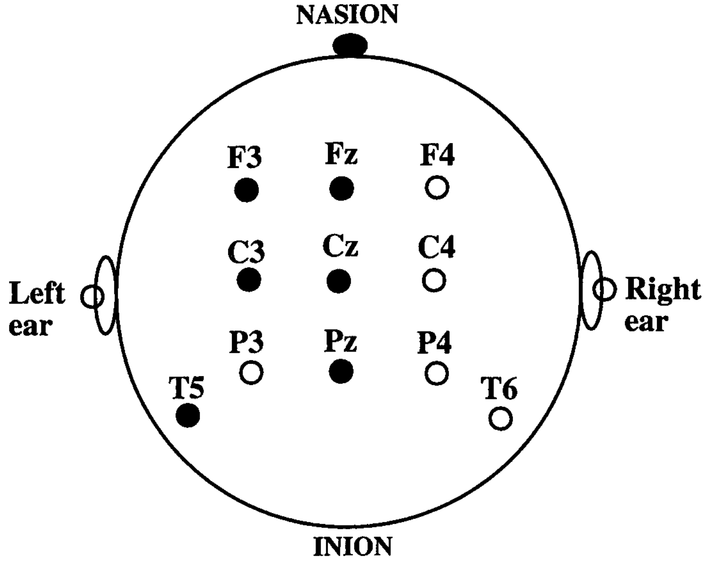


Figure 7.9. N100 amplitude measures recorded from the chronological-age control children - showing a left hemisphere focus of activation



Key: Filled-in circles indicate the regions of maximal activation, as described in the text.

Figure 7.10. Averaged evoked-potentials from a dyslexic reader during the performance of a verbal dichotic listening task.

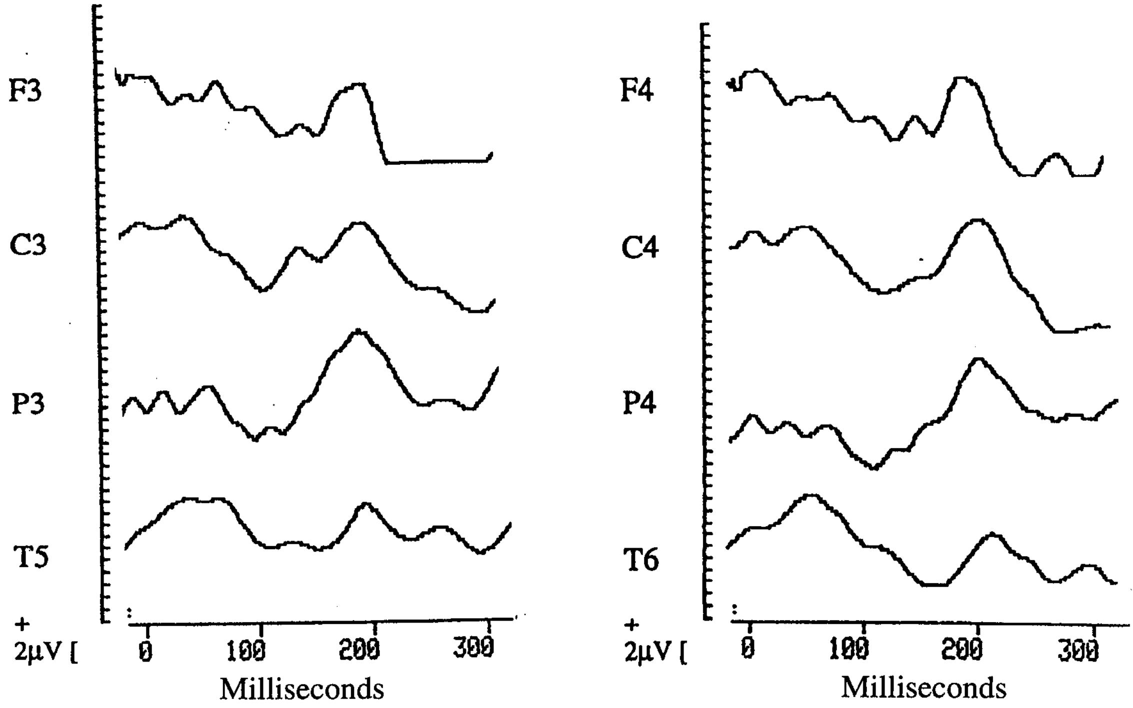
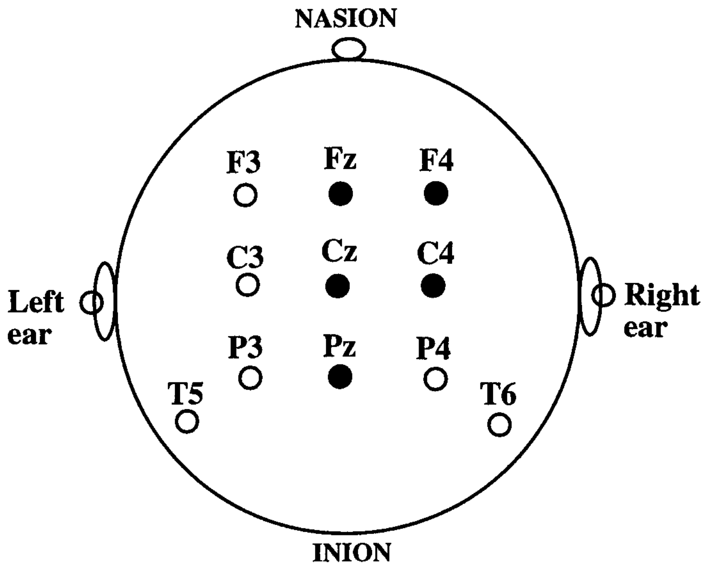


Figure 7.11. N100 amplitude measures recorded from the dyslexic readers - showing a right hemisphere fronto-central focus of activation



Key: Filled-in circles indicate the regions of maximal activation, as described in the text.

Electrical activity across each hemisphere was also found to interact with reading ability group [F (1, 34) = 8.05; p = 0.01]. Whereas both groups of readers produced significantly different levels of activation in their left and right hemispheres (both p values < 0.005), the actual pattern of activation of the two groups differed. The control readers produced significantly greater amplitudes in the *left* hemisphere (mean amplitude across the hemisphere = 9.10 μV) than in the right (mean amplitude = 8.50 μV), while the dyslexics produced significantly larger amplitudes in the *right* hemisphere (mean amplitude = 9.52 μV) than in the left hemisphere (mean amplitude = 8.91 μV). The two groups, therefore, produced approximately equal levels of activation in their left hemispheres, while the dyslexics produced the significantly greater activation in their right hemispheres (p < 0.005).

7.5.5. (a) ii. Topographic analyses:

Analysis of the normalised N100 amplitudes confirmed the findings of the previous analyses by revealing a significant cortical region by reading ability group interaction [F (10, 340) = 2.22; p = 0.05] which was once again found to reflect the left hemisphere activation bias of the control children; the dyslexics, by contrast, again showed a right hemisphere fronto-central focus of activation. A hemisphere by reading group interaction [F (1, 34) = 3.36; p < 0.005] also reflected this pattern of activation in the two samples of children.

7.5.5. (b) P200 amplitude measures:

7.5.5. (b) i. Raw waveforms:

Statistical analysis of the P200 data (presented in **table 7.4b**; see also **figures 7.8** and **7.10**) yielded a cortical region by reading ability group interaction [F (10, 340) = 3.02; p = 0.01]. This was found by post hoc analysis to indicate that the chronological-age matched control children produced a significantly greater number of inter-hemispheric differences in amplitude than the dyslexic children. This suggests a greater degree of lateralisation in the normal readers than in the dyslexics.

The good readers displayed predominantly left hemisphere activation (F3, C3 and T5 amplitudes were seen to be significantly larger than those recorded at sites C4, P4 and T6; see **figure 7.12a**). Of these the amplitudes at T5 were the largest. The focus of activation across the midline sites was in the parietal region (Pz).

The pattern of amplitude differences observed in the dyslexic children, by contrast, appeared to indicate *intra-* rather than *inter*-hemispheric differences. Within the left hemisphere the dyslexics showed the largest amplitudes in the temporo-parietal regions (P3 and T5) whereas the right hemisphere activation was more evenly distributed. As shown in **figure 7.12b**, amplitudes at site P4 were smaller than those recorded from electrodes F4, C4 and T6, which did not differ significantly in themselves.

7.5.5. (b) ii. Topographic analyses:

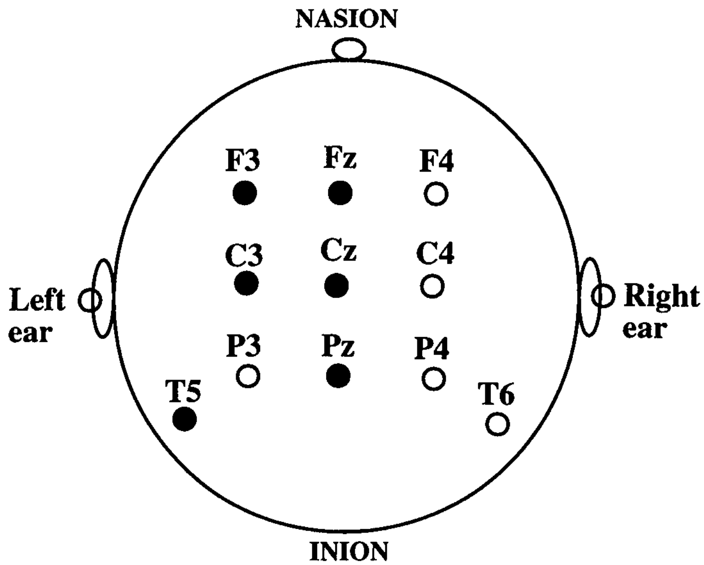
The interaction between P200 amplitudes recorded from different cortical regions and reading ability group remained significant following normalisation ($F(10, 340) = 2.21$; $p = 0.05$). This indicates that it is attributable to actual topographical differences, i.e. predominantly left hemisphere activation in the control readers and no significant inter-hemispheric differences in the dyslexics, rather than to artifactual between-group differences in amplitude.

Table 7.4b. Mean P200 amplitudes (microvolts) and standard errors for the chronological- age matched children in each recall condition.

Group	Recall	F3	F4	C3	C4	P3	P4	T5	T6	Fz	Cz	Pz
Controls	**Free**	6.43	6.85	9.58	6.27	6.80	8.14	13.02	9.01	9.46	9.84	13.03
		(±1.12)	(±2.15)	(±1.27)	(±1.23)	(±0.78)	(±1.09)	(±3.22)	(±1.66)	(±1.36)	(±1.86)	(±1.62)
	Forced	8.00	11.72	9.24	7.56	9.67	11.69	11.52	9.16	12.98	9.42	14.06
	Right	(±1.27)	(±2.39)	(±1.20)	(±1.06)	(±1.61)	(±2.09)	(±1.44)	(±1.28)	(±2.42)	(±1.32)	(±2.09)
	Forced	12.14	11.28	10.72	8.32	7.87	9.62	9.61	9.07	12.33	12.04	13.54
	Left	(±2.72)	(±2.43)	(±1.34)	(±1.42)	(±1.23)	(±1.13)	(±1.98)	(±1.21)	(±2.32)	(±1.22)	(±1.67)
Dyslexics	**Free**	8.97	10.16	8.91	10.04	9.65	7.95	9.56	8.30	10.59	10.98	10.11
		(±1.24)	(±1.40)	(±0.88)	(±1.03)	(±1.07)	(±1.67)	(±1.73)	(±1.36)	(±1.07)	(±1.84)	(±1.54)
	Forced	9.53	10.41	10.94	10.58	11.32	9.46	11.97	11.02	11.00	12.09	13.63
	Right	(±1.12)	(±1.26)	(±1.05)	(±1.45)	(±1.64)	(±1.84)	(±1.20)	(±1.41)	(±1.29)	(±1.43)	(±1.96)
	Forced	9.97	11.68	11.07	11.59	13.61	9.49	13.78	11.84	10.06	11.68	12.52
	Left	(±1.68)	(±2.11)	(±1.34)	(±2.07)	(±2.45)	(±2.23)	(±2.42)	(±2.47)	(±1.81)	(±2.54)	(±2.29)

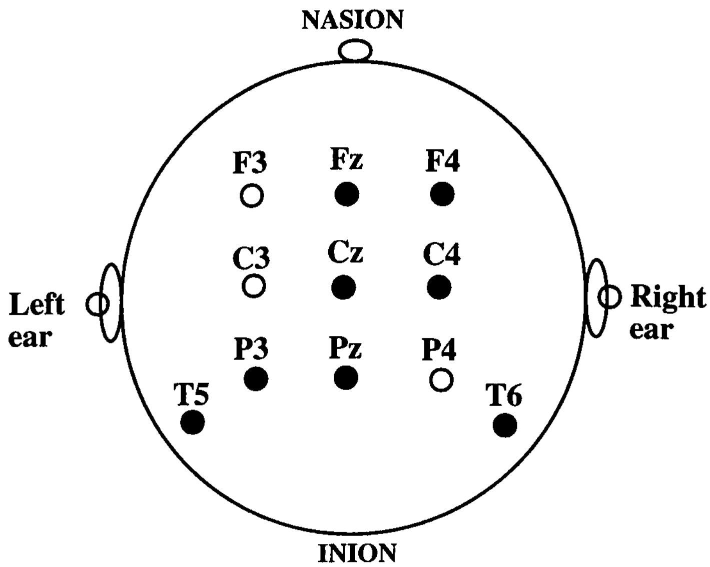
Key:
Recall: {Free - Dichotic listening free recall condition
{Forced right - Dichotic listening forced right ear recall condition
{Forced left - Dichotic listening forced left ear recall condition

Figure 7.12a. P200 amplitude measures recorded from the chronological-age control readers, showing a left hemisphere pattern of maximal activation



Key: Filled-in circles indicate the regions of maximal activation, as described in the text.

Figure 7.12b. P200 amplitudes recorded from the dyslexic children, showing a fairly diffuse pattern of activation



Key: Filled-in circles indicate the regions of maximal activation, as described in the text.

7.5.5. (c) Auditory evoked potentials: latency measures:

Analysis of the N100 latencies for the age matched dyslexic and normal readers (given in **table 7.5a**) yielded a significant interaction between dichotic listening recall condition and reading group [$F (2, 68) = 4.22$; $p = 0.03$]. This reflected the shorter latencies of the N100 waves displayed by the control children in the forced *right* condition (mean latency = 114.47 msec) than in either the free recall (mean latency = 124.06 msec) or the forced left ear response condition (mean = 126.06 msec).

The dyslexic children, however, produced shorter latencies in the forced *left* ear response condition (mean latency = 116.89 msec) than in either of the other two conditions (mean latency during free recall = 123.41 msec; mean latency during forced right ear recall = 122.2 msec).

In the forced left ear condition the controls produced significantly longer latency ERPs than the dyslexics, but this situation was reversed in the forced right ear response condition (p values < 0.005).

The demands of the three task conditions had a differential effect on the P200 latencies recorded from the two reading ability groups [$F (2, 68) = 5.95$; $p = 0.01$ - see **table 7.5b**]. Post hoc tests indicated that the controls produced longer P200 latencies in the free recall condition (mean latency = 234.52 msec) than in either the right ear (mean latency = 220.23 msec) or left ear (mean latency = 214.90 msec) forced choice conditions; the difference between the two latter conditions also proved significant ($p < 0.005$).

The dyslexics' shortest latencies were observed in the free recall condition (mean latency = 218.56 msec), their longest in the forced right response condition (mean latency = 238.57 msec).

Table 7.5a. Mean N100 latencies (microvolts) and standard errors for the chronological-age matched children in each recall condition.

Group	Recall	F3	F4	C3	C4	P3	P4	T5	T6	Fz	Cz	Pz
Controls	**Free**	134.78	132.90	132.64	125.27	120.55	127.40	141.82	151.55	143.27	137.50	141.09
		(±8.12)	(±10.63)	(±9.80)	(±11.34)	(±12.80)	(±13.62)	(±11.91)	(±11.29)	(±7.66)	(±10.10)	(±7.44)
	Forced	128.07	124.86	123.64	117.57	120.21	121.86	130.50	125.57	126.36	131.57	123.43
	Right	(±7.87)	(±6.75)	(±8.27)	(±8.45)	(±7.81)	(±9.04)	(±10.23)	(±8.15)	(±5.68)	(±7.13)	(±8.22)
	Forced	128.17	129.33	136.75	137.42	138.17	139.33	142.33	141.25	141.00	142.67	136.33
	Left	(±6.51)	(±6.30)	(±5.73)	(±7.62)	(±5.30)	(±7.45)	(±6.72)	(±10.06)	(±4.38)	(±4.36)	(±6.01)
Dyslexics	**Free**	130.70	136.60	135.46	138.64	136.30	132.75	131.27	131.27	142.91	134.91	130.09
		(±6.66)	(±6.62)	(±5.11)	(±6.35)	(±6.01)	(±9.98)	(±13.22)	(±14.35)	(±6.87)	(±4.78)	(±10.48)
	Forced	127.07	129.79	138.43	129.21	122.43	113.86	136.85	147.79	140.50	143.86	123.86
	Right	(±8.89)	(±8.91)	(±5.61)	(±7.89)	(±9.09)	(±9.37)	(±11.63)	(±12.15)	(±8.44)	(±5.96)	(±9.74)
	Forced	136.31	123.69	127.62	134.46	125.31	125.08	125.46	136.08	127.67	120.31	120.69
	Left	(±5.08)	(±6.59)	(±6.83)	(±4.68)	(±6.80)	(±7.95)	(±12.21)	(±12.09)	(±10.40)	(±6.02)	(±7.90)

Key:
Recall: {Free - Dichotic listening free recall condition
{Forced right - Dichotic listening forced right ear recall condition
{Forced left - Dichotic listening forced left ear recall condition

Table 7.5b.. Mean P200 latencies (microvolts) and standard errors for the chronological-age matched children in each recall condition.

Group	Recall	F3	F4	C3	C4	P3	P4	T5	T6	Fz	Cz	Pz
Controls	**Free**	263.91	243.55	242.91	251.70	250.00	245.36	295.30	270.18	260.45	246.45	244.45
		(±18.70)	(±11.73)	(±18.54)	(±17.93)	(±20.93)	(±23.36)	(±25.82)	(±20.31)	(±19.33)	(±17.57)	(±19.57)
	Forced	224.36	212.86	229.36	215.07	260.64	264.21	256.00	273.08	229.93	219.43	257.79
	Right	(±10.81)	(±9.82)	(±12.19)	(±11.05)	(±14.33)	(±16.47)	(±16.11)	(±16.23)	(±15.30)	(±12.63)	(±18.96)
	Forced	206.42	202.67	228.75	212.50	234.00	258.67	278.58	273.33	223.92	229.50	230.50
	Left	(±6.16)	(±5.14)	(±12.61)	(±7.33)	(±15.53)	(±15.58)	(±19.56)	(±18.05)	(±10.40)	(±9.81)	(±14.51)
Dyslexics	**Free**	225.09	211.09	226.00	232.64	241.40	252.91	250.20	272.00	237.91	223.45	250.00
		(±18.41)	(±12.28)	(±15.69)	(±14.02)	(±14.79)	(±12.92)	(±15.59)	(±15.05)	(±17.16)	(±10.96)	(±15.29)
	Forced	228.14	245.86	247.29	272.29	259.86	273.07	285.64	274.07	258.64	247.57	270
	Right	(±13.67)	(±13.93)	(±13.33)	(±15.64)	(±15.87)	(±16.32)	(±15.61)	(±15.03)	(±16.81)	(±15.27)	(±15.20)
	Forced	232.77	229.23	245.85	232.92	263.85	244.69	266.08	256.08	281.46	216.83	246.75
	Left	(±17.08)	(±13.83)	(±18.64)	(±17.68)	(±16.27)	(±17.89)	(±15.66)	(±15.16)	(±16.96)	(±9.60)	(±15.08)

Key:
Recall: {Free - Dichotic listening free recall condition
{Forced right - Dichotic listening forced right ear recall condition
{Forced left - Dichotic listening forced left ear recall condition

Furthermore, the ERP latencies produced by the normal readers were significantly shorter than those of the impaired readers in both of the forced recall conditions ($p < 0.005$), but this pattern was reversed in the free recall condition ($p < 0.005$).

7.5.6. Correlational analyses I: handedness/ phonological awareness

Analysis of the handedness measures with phonological oddity task performance (collapsed across reading groups) revealed significant correlations between the pegboard laterality indices (hand *skill*) and accuracy in the middle-sound-different [$r = 0.41$; $p = 0.01$] and last-sound-different [$r = 0.33$; $p = 0.05$] conditions, and between hand *preference* and accuracy in the middle-sound-different [$r = -0.58$; $p < 0.005$] and last-sound-different [$r = -0.50$; $p < 0.005$] conditions of the oddity task. The more positive the hand *skill* laterality index the poorer the left hand skill relative to right hand skill; greater right hand *preference* is represented by lower hand preference scores. Thus, in each instance these correlations indicated that increased dextrality was associated with greater accuracy on the phonological oddity task

7.5.7. Correlational analyses II:AEP/ dichotic listening measures

These analyses revealed significant correlations between the dichotic listening and electrophysiological measures in the dyslexic children in the free recall condition of the dichotic listening task. A negative correlation between left ear accuracy and P200 amplitude recorded over the left ($r = -0.59$; $p = 0.01$) and right ($r = -0.71$; $p < 0.005$) hemispheres indicated that greater accuracy of recall was associated with lower amplitudes.

No significant correlations emerged from analysis of the data from the control children.

7.6 Discussion of results:

The primary aim of the present study was to examine the neuropsychological context associated with differential levels of reading ability through a combination of behavioural (handedness and dichotic listening) and electrophysiological (AEP) measures. A secondary aim was to investigate the cognitive correlates of literacy (phonological processing ability, phonological memory and visual perceptual ability) in children with developmental dyslexia and in chronological-age matched control children.

7.6.1. How useful is handedness as an index of the neuropsychological substrate of competent and impaired reading?

Both groups of children displayed the overall bias in favour of the right hand expected of a sample of predominantly dextral children and no significant differences emerged in either left or right hand skill between the two groups. This failure to find any evidence of abnormal handedness in the dyslexic children, compared with normal readers of the same age, is consistent with a number of earlier studies, which found a high level of agreement between the hand skill measures of normal and impaired readers (Annett & Turner, 1974; Rutter, 1978; Annett & Kilshaw, 1984). These results would appear to argue against the notion that the dyslexic children's reading problems are the result of some sort of gross physiological dysfunction of the left hemisphere. Alternatively, it may be that this dysfunction, if it exists, is not reflected in measures of hand skill.

In spite of the lack of difference in hand skill between the chronological-age matched reading groups, the two were found to differ significantly in terms of their hand preferences. While the control children favoured the right hand for the performance of the majority of the uni-manual activities assessed in the current study, the dyslexic sample was far less dextral in its hand preferences. Even if the overtly sinistral dyslexics had been excluded from the sample these children would have continued to show a range of preferences from "pure" right-handedness to moderate right-handedness with strong left hand tendencies (Annett's (Annett & Kilshaw, 1984; Annett & Manning, 1990; Annett, 1992) "weak dextrals").

With regards to the hand preference measures, the present findings support the suggestion that a sample consisting entirely of reading-impaired children should show a raised incidence of mixed and non-right handedness (Naidoo, 1972; Annett & Turner, 1974). The hand skill data are not as easily explained, however, and in fact, they appear contrary to what would be expected on the basis of the findings of Annett and colleagues (Annett & Manning, 1990a, b; Annett, 1992b). It should be considered, though, that dyslexics have been found in excess at both extremes of the hand skill distribution (Annett & Kilshaw, 1984). It is possible, therefore, that any differences in hand skill between individual good and poor readers may have been obscured in a consideration of the overall mean hand skill of the samples. In view of Eglinton and Annett's (1994) caution that, "the effect size for atypical handedness in dyslexia is very small so it is not likely to be statistically significant except in large samples" (p. 1615), it is also possible that the relatively small sample sizes in the present investigation may be responsible for its failure to find a significant effect of hand skill.

Although different patterns of results were obtained in the current study for the hand skill and hand preference measures this does not necessarily indicate a lack of concurrent validity in the two indices of handedness (Searleman, 1980; Eling, 1983; Segalowitz, 1986). In fact, it has been suggested that different laterality indices may be specific to particular tasks and modalities, prompting Eling's (1983) conclusion that "although laterality scores may be interrelated, the relationship is apparently not as strong as has been assumed in the past" (p.145). The two should, therefore, be considered as reflecting tangential aspects of a common underlying dimension rather than as necessarily tapping the same measure.

In support of this latter suggestion is the finding that both the hand skill and hand preference measures correlated significantly with ability on the phonological oddity task (as reported by Brunswick & Rippon, 1994). These correlations indicated that increased dextrality was reflected in greater phonological awareness, and accord with Annett's (1992) report that children towards the left of the hand skill distribution are characterised by poor phonological processing abilities. Thus, these correlations appear to support the contention that an individual's phonological processing ability depends on mechanisms which favour left hemisphere representations of language and also shift the bias towards a right hand skill advantage (Annett & Manning, 1990b; Annett, 1992b).

7.6.2. How useful is the dichotic listening task as an index of the neuropsychological substrate of reading?

In partial support of previous studies employing the verbal dichotic listening paradigm (Kershner, 1988; Kershner & Micallef, 1992; Duvelleroy-Hommet *et al*, 1995), the present study observed a *trend* towards a right ear advantage for both the dyslexic children and the normal readers under forced recall, although this effect marginally missed significance. This slight bias towards the right ear, and the general failure to observe differential patterns of results in the good and impaired readers, would appear to argue against suggestions that dyslexic children are anomalously lateralised, compared with normal readers, for the perception of verbal information.

The present study's failure to find a right ear advantage in the free recall condition receives some support from the dichotic listening literature for both normal readers (Jancke *et al*, 1992; Duvelleroy-Hommet *et al*, 1995) and dyslexics (Witelson, 1977; Obrzut *et al*, 1985). In the present study this may be due to the poor performances of the children in each condition of this task. The dichotic C-V task was originally intended for use with adult subjects, and although it *has* subsequently been used with children (Hugdahl & Andersson, 1987; Bo, Hugdahl & Marklund, 1989; Brunswick & Rippon,

1994) it was performed only with some considerable difficulty by the children in the present study.

A comparison of the total number of dichotic C-Vs correctly reported by the matched samples in the three recall conditions again revealed no significant between-group differences, as found by Milberg *et al* (1981) and Aylward (1984). A number of explanations may be proposed for this rather unexpected finding. Firstly, it is possible that the result is due to a failure of the present study to take account of the heterogeneous nature of the dyslexic samples (Keefe & Swinney, 1979). Obrzut (1979), for example, reports that dyseidetic dyslexics typically show a level of accuracy similar to that of normal readers, both of whom tend to recall significantly more dichotic stimuli than dysphonetic dyslexics. Although the present study was not undertaken with the intention of distinguishing between sub-types of dyslexics (see **Section 3.1.3.** for a discussion of the perils of sub-typing), by treating the dyslexic children in the present study as a homogeneous group it is possible that any differences between individual dyslexics and the control readers may have been obscured. A second possibility is that this result is a factor of the stimuli employed in the present study. Differential ear advantages in normal and dyslexic children are reported far less frequently in response to single C-V syllables than to other types of dichotically presented stimuli (Mercure & Warren, 1978; Obrzut, 1989). Thirdly, any differences in phonological discrimination ability which exist between the good and dyslexic readers may have been obscured by the generally poor performances of the two groups on this task. Finally, it may be that the C-V dichotic listening task employed in the present study failed to tap the particular cognitive deficits which underlie dyslexia.

7.6.3. What of the electrophysiological measures?

A number of significant between-group differences emerged from analysis of the N100 and P200 measures, all of which indicated some form of anomalous activation in the dyslexic children. Overall the control readers displayed a pattern of predominantly left hemisphere activation, i.e. larger amplitudes and shorter latencies in the left than the right hemisphere. Such a pattern of activation in normal subjects in response to linguistic stimuli receives support from the literature (Tenke *et al*, 1993; Ahonniska *et al*, 1993; Brunswick & Rippon, 1994) and is in line with expectations regarding the left hemisphere mediation of linguistic processing (Porac & Coren, 1981; Obrzut, 1989). Furthermore, this effect emerged irrespective of ear of report, and during the simultaneous stimulation of the two ears, thus arguing against possible explanations based on the differential strength and magnitude of the contra-lateral and ipsi-lateral auditory pathways (Andreassi *et al*, 1975; Connolly, 1985; Alho *et al*, 1994).

The dyslexic children, in contrast, showed no such bias towards the left hemisphere. Instead these poor readers displayed either no particular lateralised effects or a bias towards larger amplitude and longer latency AEPs in the right hemisphere (see also Brunswick & Rippon, 1994). This latter result is of particular interest as it reflects the source of the differences between the good and poor readers. Whereas the two groups of children produced similar patterns of activation in their left hemispheres it was the dyslexic children's significantly larger amplitude waveforms in the right hemisphere which were responsible for producing the right hemisphere focus of activation observed in these children (as reported by Naylor, 1987; Naylor, Wood & Flowers, 1990).

In view of the similarities in the behavioural measures of the two groups of children, and of their comparable patterns of left hemisphere activation in the electrophysiological measures, it is suggested that both the good and the poor readers are lateralised to the left hemisphere for the mediation of linguistic processing. Explanations for the anomalous activation across the right hemispheres of the dyslexics will be couched, therefore, in terms of between-group differences in processing strategy, or the differential allocation of attentional resources by the two groups rather than differences in terms of functional lateralisation.

One possible explanation has its origin in Goldberg and Costa's (1981) model of hemispheric specialisation. This model suggests that the left hemisphere is specialised for automatic, routinised processing whereas the right hemisphere is involved in the processing of novel and complex information, "when no task-relevant descriptive system or code is immediately available in the child's cognitive repertoire" (Dool, Stelmack & Rourke, 1993). According to this theory, during the early stages of acquiring a novel skill the right hemisphere is critically involved in the acquisition of the necessary "descriptive system". With increasing competence in the skill, however, the descriptive system is established and a shift in hemispheric superiority occurs as the left hemisphere takes over the application of the now routinised codes. This process may be conceptualised in physiological terms as reflecting "adaptive pruning" (Naylor *et al*, 1990) of superfluous neurons in the development of high level cognitive processing skills (Ellis *et al*, 1991; Brown *et al*, 1994). This may be related to the current finding of larger right hemisphere amplitudes in the dyslexic children than in the control group. That the phonological discrimination skills of the dyslexic children are inferior to those of the chronological-age matched controls has already been established (**Section 7.5.3.**). The suggestion that the dyslexics process the dichotic stimuli with greater difficulty and with less automaticity than the competent readers is understandable, therefore, and readily accounts for the greater involvement of the right hemisphere in the brains of the dyslexics.

Alternatively it may be that the greater involvement of the right hemisphere in the brains of the dyslexics than the controls may reflect the inappropriate allocation of attentional resources in the poor readers. It may be, for example, that the simultaneous presentation of stimuli to the two ears serves to activate both cerebral hemispheres. In normal readers the involvement of the non-dominant hemisphere is suppressed by the dominant hemisphere, possibly mediated by the corpus callosum (see **Section 4.4.2 (c)** for a discussion of the hypothesised role played by this structure in the mediation of attention). This suppression does not occur in the brains of the dyslexic children. Support for this conjection derives from previous behavioural evidence which has indicated an inability in dyslexics to suppress the involvement of the right hemisphere during the processing of verbal stimuli (Hugdahl & Andersson, 1987; Boliek *et al*, 1988; Obrzut, 1991). Whether or not this excess activation in the non-dominant hemisphere would normally serve to reduce the efficiency of the cognitive processing is not possible to determine from the present study, however, as firstly, the ERP components measured in this study preceded the onset of cognitive processing, and secondly, as mentioned previously, the poor performances on the behavioural task may have masked any differential perceptual abilities of the good and poor readers.

It would appear, therefore, that greater processing competence is associated with lesser activation, whether across the right hemisphere (Dool *et al*, 1993) or across the neocortex as a whole (Smith, Michalewski, Brent & Thompson, 1980; Naatanen & Picton, 1987). It is also reported that ERP amplitude increases as a function of the processing demands of a behavioural task (Duncan *et al*, 1994). Accordingly, the correlational finding of the present study revealed that within the dyslexic sample, greater accuracy of recall on the dichotic listening task was associated with lower amplitude AEPs across the scalp. Wood and colleagues (Wood, 1983, 1990; Naylor *et al*, 1990; Wood *et al*, 1991) have interpreted negative correlations between task accuracy and cerebral activation as indicating that, in contrast to individuals in whom a particular type of processing is well automatised, those who experience difficulty with a task expend greater effort (including neural effort) to perform it (see Harter, Anllo-Vento, Wood & Schroeder, 1988a; Harter, Diering & Wood, 1988b). This hypothesis is further supported by the ERP latency results. The longer latencies of the dyslexic children's ERPs would indicate a greater degree of difficulty in the processing of the task than that experienced by the control children (as reported by Holcomb, Ackerman & Dykman, 1985; Alonso, Navarro & Abad, 1990; Fawcett, Chattopadhyay, Kandler, Jarratt, Nicolson & Proctor, 1993).

On the basis of the above evidence it is suggested that although the dyslexics on the whole produced greater levels of activation than the control children (as reported by

Foale, Baldeweg, Richardson & Gruzelier, 1995) it is the dyslexics who produced the lower levels of activation (i.e. who were required to expend less effort to perform the dichotic listening task) who scored more highly on the behavioural task. This effect was observed in the P200 component of the waveform which is allegedly reflective of the allocation of processing resources (see **section 4.4.5**; also Knight, Hillyard, Woods & Neville, 1980; Vaughan *et al*, 1983; Naatanen & Picton, 1987). It is possible, therefore, that whereas the dyslexic children in general experienced difficulty in suppressing inappropriate activation during cognitive processing (Hugdahl & Andersson, 1987; Boliek *et al*, 1988; Obrzut, 1991), those with greater accuracy for reporting stimuli heard in the left ear were the ones who *were* able to suppress this excessive activation, as reflected in the lower amplitude ERPs.

7.6.4. Were the good and poor readers distinguishable on the basis of phonological processing ability?

In accordance with the findings from the longitudinal study (**chapter 6**), overall the children performed with greater accuracy in the two rhyming conditions (middle- and last-sound-different) of the phonological task than in the alliterative awareness (first-sound-different) condition, as reported by Bradley and Bryant (1978; 1983; see **Section 6.6.1 (c)** for a discussion of this issue).

No significant differences were obtained in the present study between the poor readers and the matched controls in the first-sound-different condition of the phonological oddity task. This result is in surprising contrast to that of previous researchers who have reported significantly poorer alliterative awareness in dyslexic children compared with normal readers (Bradley & Bryant, 1978; Bryant *et al*, 1990). There was a *tendency*, however, for the chronological-age matched children in the present study to perform the task with greater competence than the dyslexics. This tendency *may* have emerged as a significant difference, in the predicted direction, if the task had consisted of a greater number of trials. As this particular task consists of only 8 trials per condition, the present finding may be a product of the generally poor performance of both samples of children over relatively few trials (see also Webster & Plante, 1992).

Significant differences *were* found between the good and poor readers in the rhyming conditions of the phonological oddity task. The chronological-age matched good readers out-performed the dyslexics in both the middle-sound-different and the last-sound-different conditions of the task; these results support the findings of Bradley (1980) and also previous reports that dyslexics display an impaired ability at detecting rhymes (Bradley & Bryant, 1978; MacLean *et al*, 1987) and producing them (Lundberg *et al*, 1980). See **Section 3.2** for a discussion.

7.6.5. Can the two groups be discriminated on the basis of any other cognitive ability?

Contrary to expectations, reading ability was found to exert no significant influence over the children's performance on any of the remaining psychometric tests.

The failure of the present study to detect any significant between-group differences on the measures of visual perceptual ability - the block design task and the matching of letter-like forms task - may be accounted for in a number of ways. With regard to the latter task it may be that any extant differences in ability between the two groups were masked by the fact that the children performed this task at ceiling level. The task is designed for use with children between the ages of 4 and 9 years (Elliott *et al*, 1983); the children in the present study were at the upper limit of this age range. It is possible, therefore, that any verbal-visual perceptual deficits which may be experienced by the dyslexic readers (see **Section 3.4**) are not sufficient to seriously impair their performance on this relatively simple visual task. Considering the two measures together it may be that the absence of between-group effects (in support of similar findings by Thomson, 1982; Grogan, 1986; Moore *et al*, 1995) indicates that visual perceptual deficits, of the sort tapped by these particular tasks, are not implicated in the reading impairments of the dyslexic children in the present study.

The absence of a reading-group effect on the digit span test is surprising in the light of previous studies which report that, compared to normal readers, dyslexics tend to show reduced auditory memory span (Mann *et al*, 1980; Liberman *et al*, 1982). Others have argued, however, that while dyslexics as a group tend to display poorer memory skills than normal readers, not all dyslexics show these memory impairments. Torgesen & Houck (1980), for example, report cases of dyslexics with memory capacities comparable to those of normal readers, as reported in the present study. Similarly, McDougall *et al* (1994) report that when the effects of rate of articulation are accounted for phonological memory ceases to distinguish between readers of differing ability. These authors argue, therefore, that speech rate, rather than memory span, is the more accurate predictor of individual differences in single word reading ability. This issue remains controversial, however (see **Section 2.4.5.**).

7.6.6. Summary of findings from Study 1 and future directions:

In conclusion, the results from the hand skill measure and the dichotic listening task indicate that the chronological-age matched competent and impaired readers are indistinguishable in terms of *direction* of cerebral functional organisation. The less extreme right hand tendencies of the dyslexic children on the hand preference measures *may* reflect subtle differences in *degree* of lateralisation, however.

Between-group differences in the relative involvement of the left and right cerebral hemispheres in the processing of verbal dichotic information emerged from analysis of the electrophysiological data. These data indicated that whereas the left hemisphere activation of the good and poor readers was comparable, the two groups were distinguishable on the basis of their right hemisphere activation. The dyslexic children produced significantly higher amplitude and longer latency N100 and P200s within this hemisphere than the control children. The suggestion is, therefore, that the difficulties experienced by dyslexic children may be the result of a software (*processing*) problem rather than a hardware (*structural*) one. Speculation has rested on the use of age-*in*appropriate processing strategies by the dyslexic children.

Specific processing deficits of the dyslexic children emerged from analysis of the cognitive measures. These children were impaired, for example, in the ability to differentiate between words on the basis of rhyme but not on the basis of alliteration. This is shown by the divergence of the scores from the two samples of children in the middle- and last-sound-different phonological oddity task conditions, alongside their comparable performances in the first-sound-different condition and also on the dichotic listening task. These findings have been related to the neuropsychological characteristics of the children via the handedness and electrophysiological measures.

The extent to which these findings provide an accurate delineation of the relationship between the cognitive and neuropsychological profiles of competent and impaired readers is unclear on the basis of the present study. It may be, for example, that observed differences between the two samples are the result of their different reading levels. Alternatively, it may be that their divergent reading abilities are a product of their differential cognitive and neuropsychological characteristics. This is investigated in the next study.

STUDY2:

As discussed in **Section 7.6**, evidence concerning the possible physiological basis of developmental dyslexia is equivocal. No significant differences emerged between the competent and impaired readers in terms of handedness (although the dyslexics proved less right hand *preferent* than the control children this was not reflected in the hand *skill* measures) or lateralised performance on the dichotic listening task. In spite of the general absence of behavioural differences, the electrophysiological measures highlighted striking between-group effects. The cortical activation of the control children showed a predominantly left hemisphere focus during the dichotic listening task while the corresponding activation in the dyslexic children displayed a right hemisphere bias. These results would appear to offer partial support to suggestions of anomalous functional lateralisation in dyslexic children, at least during the perception of C-V syllables. Possible causes for this differential pattern of results in the two groups of chronological-age matched good and poor readers have been discussed.

The validity of these findings may be questioned, however, on the basis of a methodological issue which has received a great deal of attention in the reading research literature but relatively little consideration in the neuropsychology literature. This issue is the selection of appropriate control children in investigations into the aetiology of reading impairments.

Traditionally the most popular design of study for comparing the abilities of good and poor readers is the chronological-age match paradigm, as employed in the previous study (also Siegel & Linder, 1984; Morais, Cluytens, Alegria & Content, 1986; Siegel & Ryan, 1988). Such studies compare good and poor readers matched in every respect except for their differential reading levels and are useful for the identification of a *sine qua non* of successful reading development. These studies have their limitations, however, in that they reveal nothing about causality. A dyslexic child's inability to perform a particular task which poses no problem to a good reader of the same age may indicate one of two possibilities: (1) that the skill required for the performance of this task underlies the child's reading difficulties, or (2) that the necessary ability is normally, either directly or indirectly, a result of reading competence. Which of these possibilities is the correct one is impossible to determine on the basis of a chronological-age match design (see Bryant & Goswami, 1986; Goswami & Bryant, 1990).

In the light of these limitations researchers have increasingly adopted the reading-age match design (Bryant & Goswami, 1986; Johnston *et al*, 1987; Holligan & Johnston, 1988). Such studies compare the abilities of poor readers with those of younger children reading at the same level. By equating the two groups' reading abilities it is possible to dismiss explanations for observed differences based on differential reading levels, as there is no difference. Studies in which the cognitive abilities of dyslexic children have been found to be comparable to those of reading-age match control children have offered some support to developmental lag theories of dyslexia (Beech & Harding, 1984; Treiman & Hirsh-Pasek, 1985; Stanovich *et al*, 1986).

To control for the limitations of the chronological-age match paradigm the present study employed the reading-age match design in an attempt to shed light on the cognitive and neuropsychological characteristics necessary to support successful reading development, and also on the direction of causality between the various measures. For this purpose the same behavioural and electrophysiological measures as were employed in the previous study were again employed (see **Section 7.2.2.**). The conceptual expectations underlying the present study suggested that if developmental dyslexia is the result of a maturational lag in cerebral functional development (see **Section 4.3**) then dyslexic children should show a pattern of cognitive abilities comparable to that of reading-age matched children. If the dyslexics' reading problems are the result of some sort of hemispheric anomaly, however, then these children would be expected to differ in their cognitive profiles from both the younger and older normal readers.

7.7 Method:

7.7.1. Subjects:

The subject samples in this study comprised 9 dyslexic children and 9 control children matched as closely as possible with the dyslexics on the basis of reading-age and sex; the ages of these children ranged between 8:03 and 11:03 years with a mean of 9:39 years (± 0.97). Ideally larger samples of children would have been tested in this study, but a certain degree of difficulty was experienced in recruiting subjects able to attend the university for an hour's testing session. In view of the fact that the number of individuals included in ERP studies is normally quite small (the methodological and temporal demands of these studies usually prohibit the testing of large numbers of subjects; see, for example, Nobre & McCarthy, 1994; Alho *et al*, 1994; Lovrich *et al*, 1994), 18 was considered to be an acceptable sample size in the present study.

The dyslexic children (7 boys and 2 girls) were again recruited via the Specific Learning Difficulties Support Service. Their ages ranged between 9:04 and 11:03 years (mean age = 9.95 years ± 0.77) and the mean reading-age of the sample was 8:17 years (± 0.34; indicating a mean discrepancy of 1:78 years between chronological-age and reading-age). Hand preference ratings indicated a mix of strong dextrals to dextrals with weak sinistral tendencies (ratings between 1 and 3; mean score = 2.44 ± 0.88). These children had a mean verbal IQ (according to the British Picture Vocabulary Scale) of 101.75 (±5.74).

The reading-age matched sample (recruited from a local school) also comprised 7 boys and 2 girls, with a mean chronological-age of 8:84 years (± 0.84; range = 8:03 - 10:05). Hand preference scores for this sample again revealed pure dextral to dextral with mild left hand tendencies (mean score = 1.22 ± 0.67). These children displayed a mean reading-age of 8:50 years (± 0.51 years), showing that they were reading at approximately the level expected on the basis of their chronological-ages.

English was the first language of all of these children and none had any neurological, psychiatric or hearing impairments. The imbalance of these samples with regards to sex is again acknowledged (see **Section 7.2.1.**).

7.7.2. Stimuli and apparatus:

To allow for comparisons between the reading-age matched children in the present study and the chronological-age matched children in the previous study, the measures used in this study were the same as those employed previously (see **Section 7.2.2.**).

7.8. Procedure:

The children were tested individually in the psychophysiology laboratory of the University of Warwick according to the procedure outlined in **Section 7.3**.

7.9. Data reduction:

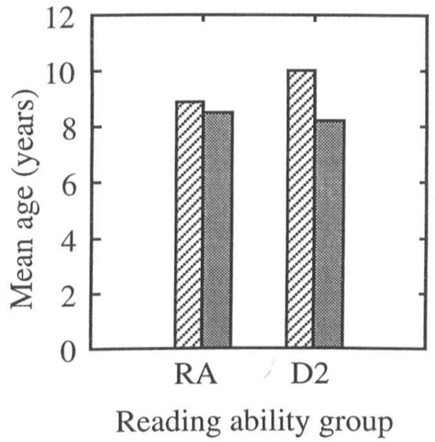
The behavioural and electrophysiological measures were quantified according to the scoring instructions provided (see **Section 5.5**). These data were entered into an Apple Macintosh Systat package and analysed in the same manner as the data in the previous study (see **Section 7.4**).

7.10. Results:

7.10.1. Sample characteristics

In line with expectations the dyslexics and the reading-age control children did not differ in terms of reading-age ($p = 0.10$) but the dyslexics were significantly older than the normal control readers [$F(1, 15) = 8.91$; $p = 0.01$]. This is illustrated in **figure 7.13**.

Figure 7.13. Mean chronological- and reading-ages of the normal and impaired readers



Key:

Reading age Chronological age

RA = reading-age matched good readers; D2 = dyslexic readers

7.10.2. Indirect laterality measures

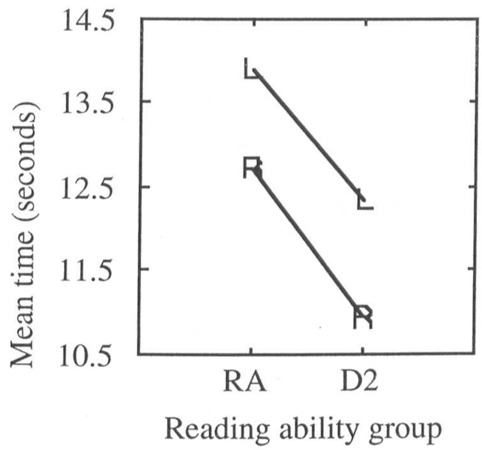
Within-group analyses of the children's pegboard completion times (see **table 7.6** and **figure 7.14**) revealed that the right hand times were significantly faster than those of the left hand for both the controls [$F(1, 8) = 15.03$; $p < 0.005$] and the dyslexics [$F(1, 8) = 31.60$; $p < 0.005$].

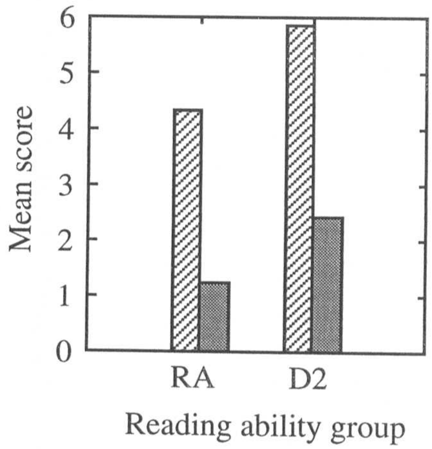
Table 7.6. Mean ages and handedness measures for the reading-age matched samples (with standard errors).

Reading group	Chronological-age: years	Reading-age: years	Peg Left: seconds	Peg Right: seconds	Pegboard Laterality Indices	Hand Preferences
Reading- age controls	8.84 (±0.28)	8.50 (±0.17)	13.91 (±0.52)	12.74 (±0.41)	4.34 (±0.99)	1.22 (±0.22)
Dyslexic readers	9.95 (±0.26)	8.17 (±0.11)	12.35 (±0.45)	10.94 (±0.21)	5.86 (±0.92)	2.44 (±0.29)

Key: Reading-age = as determined by the British Ability Scales Word Reading test; Peg Left = left hand mean completion time on the pegboard; Peg Right = right hand mean completion time on the pegboard; Pegboard Laterality Indices = ((peg left-peg right)/(peg left+pegright)) * 100; Hand Preferences = score on the Annett Hand Preference questionnaire.

Figures 7.14 and 7.15. Mean hand times for the completion of the pegboard, hand skill laterality indices and hand preference measures





Key: Pegboard completion times: R = Right hand; L = Left hand

Hand preference   Laterality indices

RA = reading-age matched good readers; D2 = dyslexic readers

Significant differences were found between these two samples of children on the hand skill measure: for the right hand [F (1, 15) = 15.96; p < 0.005] and the left hand [F (1, 15) = 5.09; p = 0.04]. In each case this reflected the faster completion times of the dyslexic children compared with the younger normal readers. No significant between-group differences emerged for the hand skill laterality indices (p = 0.29) although the dyslexics proved significantly more left hand preferent than the control children [F (1, 15) = 10.47; p = 0.01]. This is illustrated in **figure 7.15**.

7.10.3. Psychometric measures

Analysis of the data from the phonological oddity task (**table 7.7**), collapsed across reading groups, showed that all of the children performed with greater accuracy in the last-sound-different [F (1, 17) = 32.12; p < 0.005] and middle-sound-different [F (1, 17) = 13.42; p < 0.005] conditions than in the first-sound-different condition. No difference in accuracy was found between the middle- and last-sound-different conditions (p = 0.14).

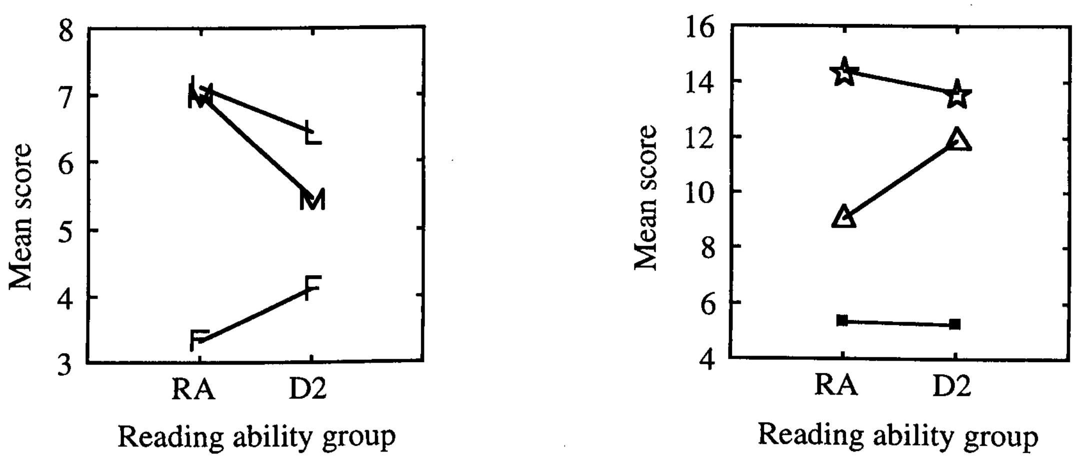
Table 7.7. Mean scores for the reading-age matched children on the psychometric test battery (with standard errors).

Reading group	First-sound-different	Middle-sound-different	Last-sound-different	Digit span	Block design	Matching of letter-like forms
Reading-age controls	3.33 (±0.41)	7.00 (±0.29)	7.11 (±0.39)	5.30 (±1.03)	9.00 (±1.23)	14.33 (±0.29)
Dyslexic readers	4.11 (±0.78)	5.44 (±0.58)	6.44 (±0.29)	5.27 (±0.67)	11.89 (±0.66)	13.56 (±0.56)

Key: First-sound-different = Bryant & Bradley first-sound-different condition; Middle-sound-different = Bryant & Bradley middle-sound-different condition; Last-sound-different = Bryant & Bradley last-sound-different condition.

No differences were found between the children in either the last-sound-different (p = 0.19) or first-sound-different (p = 0.36) conditions (**figure 7.16**), but the younger normal readers performed the task with greater accuracy than the dyslexics when the words were differentiable on the basis of their middle sounds [F (1, 15) = 6.44; p = 0.02].

Figures 7.16 and 7.17. Mean accuracy on the psychometric measures, by reading group.



Key: Phonological oddity task: F = First-sound-different; M = Middle-sound-different; L = Last-sound-different condition mean scores

☆ Letter-like forms Δ Block design ▪ Digit span

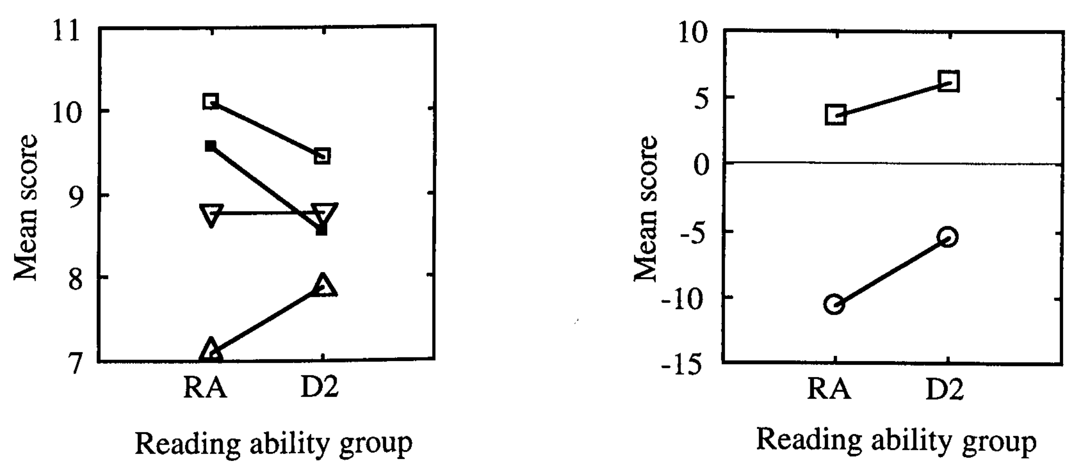
RA = reading-age matched good readers; D2 = dyslexic readers

Analysis of the data from the block design task indicated that the older, dyslexic children performed this task with greater competence than the younger control children [F (1, 16) = 4.33; p = 0.05] but no further differences emerged as significant from analysis of the psychometric data (see **table 7.7** and **figure 7.17**).

7.10.4. Direct laterality measures I: dichotic listening

No significant between-group differences emerged from analysis of recall accuracy on the dichotic listening task (see **table 7.8** and **figure 7.18**). The only significant ear effects to emerge from analysis of the dichotic listening data were in the laterality indices for the dyslexics [F (1, 7) = 9.23; p = 0.02] and for the reading-age matched control children [F (1, 7) = 5.38; p = 0.05]. These results reflect the fact that both groups showed a bias towards the right ear in the forced recall condition which was absent in the free recall condition (**figure 7.19**).

Figures 7.18 and 7.19. Mean accuracy and ear advantage indices in the free and forced ear recall conditions of the dichotic listening task



Key:

Mean accuracy: ▽ Forced Right △ Forced Left ■ Free Right ▫ Free Left

Laterality indices: ▫ Free Recall ○ Forced Recall

RA = reading-age matched good readers; D2 = dyslexic readers

Table 7.8. Accuracy on the dichotic listening task - numbers of correct responses and ear advantage indices (with standard errors) for the reading-age matched groups.

Reading group	**Free recall: Left ear**	**Free recall: Right ear**	**Forced recall: Left ear**	**Forced recall: Right ear**	**Free recall: E.A.I.**	**Forced recall: E.A.I.**
Reading-age controls	10.11 (±0.56)	9.56 (±0.92)	7.11 (±0.54)	8.78 (±0.60)	3.71 (±3.82)	-10.61 (±5.52)
Dyslexics	9.44 (±0.58)	8.56 (±0.92)	7.89 (±0.56)	8.78 (±0.55)	6.10 (±3.94)	-5.52 (±4.75)

Key: Free recall E.A.I. = Free recall condition ear advantage indices; Forced recall E.A.I. = Forced recall condition ear advantage indices.

7.10.5. Direct laterality measures II: Auditory Evoked Potentials

7.10.5. (a) N100 amplitude measures:

Mean N100 amplitudes recorded during the three dichotic listening recall conditions are displayed in **table 7.9a** for the dyslexic and control children (see also **figures 7.20** and **7.22**).

7.10.5 (a) i. Raw waveforms:

A significant cortical region by reading group [$F (10, 160) = 6.77$; $p < 0.005$] interaction indicated that the reading-age control children displayed bilateral frontal (F3 and F4) and left hemisphere fronto-centro-temporal foci of activation (amplitudes recorded from electrodes F3, C3 and T5 were found to be significantly greater than those recorded from C4, P3, P4 and T6; see **figure 7.21**).

No lateralised inter-hemispheric differences were observed in the ERPs recorded from the dyslexic children (**figure 7.23**).

Amplitudes recorded over the left and right hemispheres also varied according to reading group [$F (1, 16) = 22.89$; $p < 0.005$], such that the dyslexic children produced significantly larger amplitude ERPs than the control readers, in both their left ($p = 0.02$) and right hemispheres ($p < 0.005$). Furthermore, within group differences were observed such that the good readers produced significantly greater amplitude ERPs in the left hemisphere (mean = 9.58 μV) than in the right (mean = 6.96 μV; $p = 0.01$) whereas the dyslexic children showed no such pattern of lateralisation (left hemisphere mean amplitude = 10.28 μV, right hemisphere mean amplitude = 10.66 μV; $p = 0.51$).

Table 7.9a. Mean N100 amplitudes (microvolts) and standard errors for the reading-age matched children , by recall condition.

Group	Recall	F3	F4	C3	C4	P3	P4	T5	T6	Fz	Cz	Pz
Controls	**Free**	11.29	18.94	10.06	4.61	6.45	6.03	12.06	7.68	24.12	14.18	14.93
		(±2.62)	(±7.29)	(±2.05)	(±0.83)	(±1.51)	(±2.25)	(±2.10)	(±2.09)	(±5.98)	(±5.35)	(±5.07)
	Forced	9.53	9.43	7.90	5.34	5.91	5.95	10.71	5.57	19.58	11.48	17.17
	Right	(±1.74)	(±1.37)	(±1.41)	(±1.47)	(±0.92)	(±1.55)	(±1.34)	(±1.30)	(±6.21)	(±3.70)	(±3.69)
	Forced	16.00	14.18	10.04	4.19	5.47	7.52	9.59	6.11	19.97	7.31	20.43
	Left	(±5.22)	(±4.18)	(±1.92)	(±0.64)	(±0.81)	(±1.61)	(±2.27)	(±1.17)	(±4.94)	(±1.97)	(±5.99)
Dyslexics	**Free**	11.74	13.56	12.25	12.60	9.51	8.31	9.99	10.18	11.31	9.55	10.19
		(±1.59)	(±0.91)	(±1.52)	(±1.09)	(±1.37)	(±0.26)	(±1.53)	(±1.58)	(±2.03)	(±1.60)	(±0.92)
	Forced	10.68	8.34	11.28	10.75	9.34	7.47	10.70	14.72	11.19	12.38	9.04
	Right	(±2.96)	(±2.40)	(±2.34)	(±2.26)	(±1.93)	(±2.39)	(±0.82)	(±0.30)	(±0.60)	(±1.25)	(±3.15)
	Forced	10.71	14.13	11.30	11.86	8.79	6.93	7.12	9.04	12.33	9.66	9.91
	Left	(±1.27)	(±1.24)	(±1.88)	(±1.59)	(±1.31)	(±1.13)	(±0.79)	(±0.72)	(±1.28)	(±1.86)	(±0.96)

Key:
Recall: {Free - Dichotic listening free recall condition
{Forced right - Dichotic listening forced right ear recall condition
{Forced left - Dichotic listening forced left ear recall condition

Figure 7.20. N100 and P200 components of the evoked-potential from a reading-age matched control reader at the lateralised cortical regions.

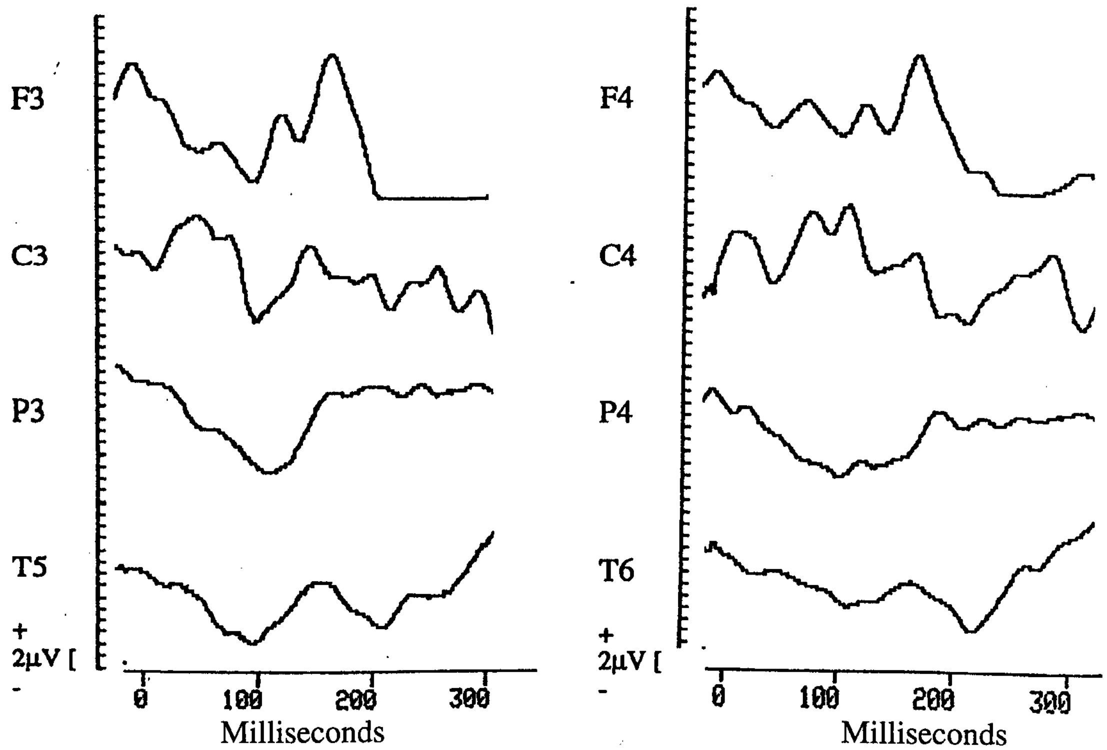
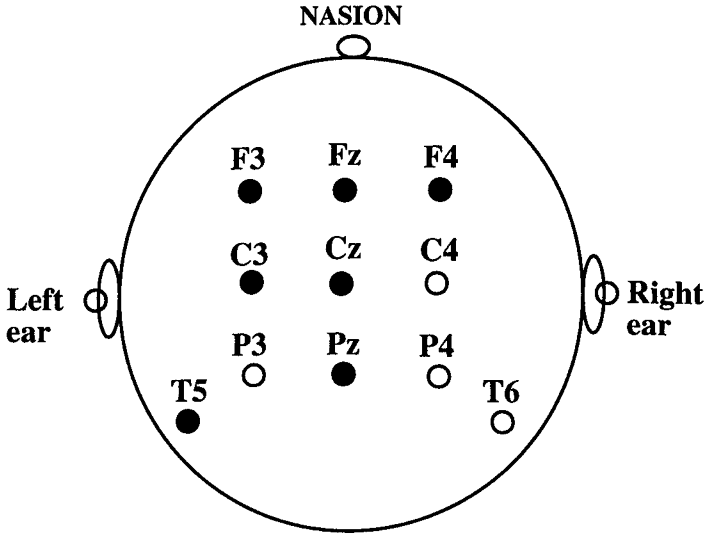


Figure 7.21. N100 ERP amplitudes recorded from the reading-age matched competent readers - showing bilateral frontal and left hemisphere fronto-centro-temporal activation



Key: Filled-in circles indicate the regions of maximal activation, as described in the text.

Figure 7.22. Averaged evoked-potentials from a reading-age matched dyslexic reader during the dichotic listening task.

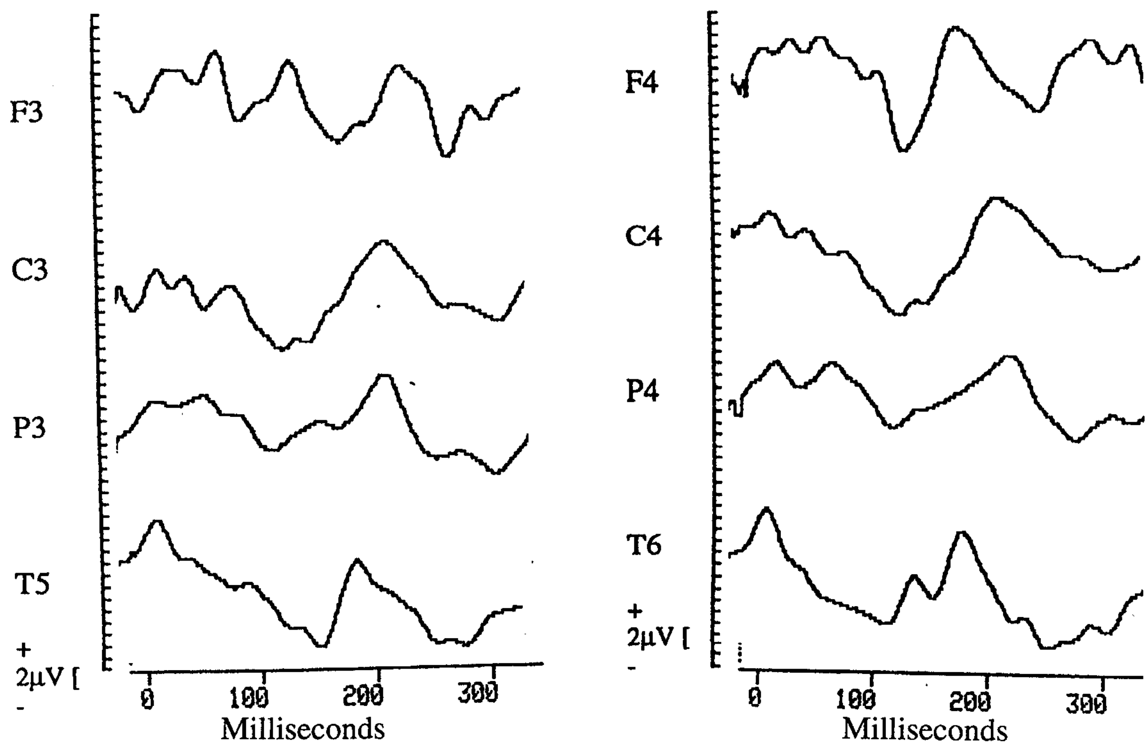
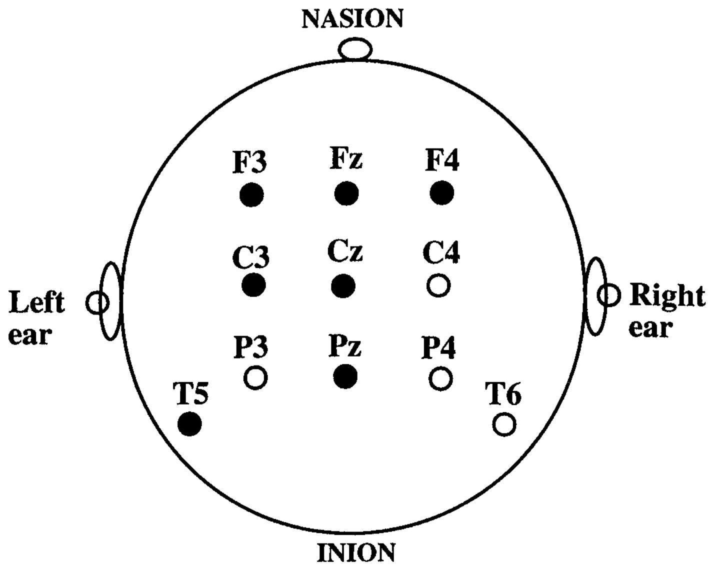


Figure 7.23. N100 ERP amplitudes recorded from the dyslexics - showing no lateralised activation



Key: Filled-in circles indicate the regions of maximal activation, as described in the text.

7.10.5 (a) ii. Topographic analyses:

The previously reported interactions between cortical region and reading ability group [F (10, 160) = 5.33; p < 0.005] and between hemisphere and reading group [F (1, 16) = 8.53; p = 0.01] both remained significant with the normalised data. These data again indicate that the differential patterns of activation of the good and poor readers are a function of actual differences in scalp distribution independent of possible between-group differences in level of activation.

7.10.5 (b) P200 amplitude measures:

7.10.5 (b) i. Raw waveforms:

P200 amplitudes recorded at different electrode sites (shown in **table 7.9b** and in **figures 7.20** and **7.22**) again interacted with reading ability group [F (10. 160) = 4.57; p < 0.005], indicating that the dyslexic children are less lateralised in their pattern of neural activation than the control readers.

The younger control children displayed their greatest amplitude ERPs in the frontal, central and temporal regions of the left hemisphere (shown in **figure 7.24a**) and at the midline sites (especially Pz). The only lateralised activation in the brains of the dyslexic children was in the right hemisphere frontal region (F4: p < 0.025; see **figure 7.24b**).

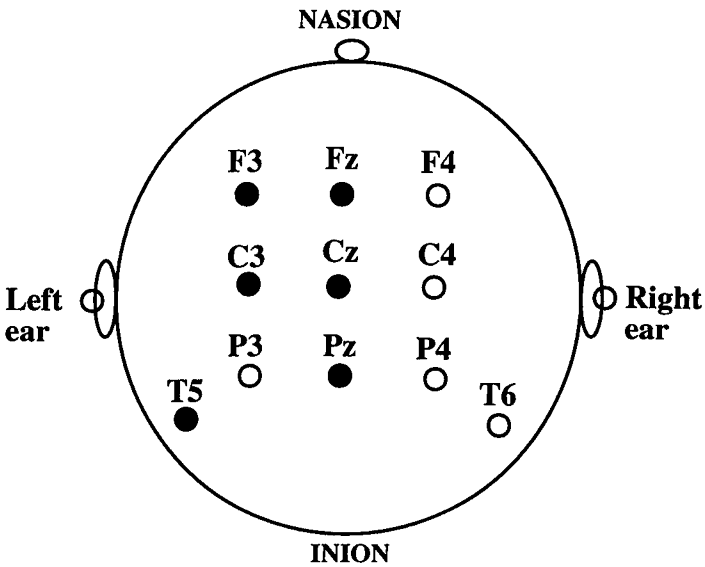
A comparison of the amplitudes recorded across the two cerebral hemispheres of the two groups of children revealed that whereas the good readers produced significantly larger amplitudes in the left hemisphere (mean amplitude = 9.48 μV) than in the right (mean amplitude = 8.39 μV; p < 0.005), this pattern is reversed in the dyslexics who produced ERPs of larger magnitude in the right hemisphere (mean amplitude = 11.28 μV) than in the left (mean amplitude = 10.88 μV; p = 0.01). This finding is reflected in the form of a significant hemisphere by reading group interaction [F (1, 16) = 5.89; p = 0.03]. Over both hemispheres the level of activation produced by the dyslexics was greater than that of the control readers (both p values < 0.005).

Table 7.9b Mean P200 amplitudes (microvolts) and standard errors for the reading- age matched children , by recall condition.

Group	Recall	F3	F4	C3	C4	P3	P4	T5	T6	Fz	Cz	Pz
Controls	**Free**	6.82	10.69	9.10	3.77	5.94	9.48	13.41	8.63	10.92	9.97	11.61
		(±1.27)	(±3.92)	(±1.56)	(±0.88)	(±0.71)	(±1.02)	(±5.42)	(±1.12)	(±2.34)	(±3.83)	(±1.37)
	Forced	6.73	6.99	6.59	4.09	6.78	9.40	6.67	7.22	9.04	4.67	17.16
	Right	(±0.92)	(±0.95)	(±1.22)	(±0.57)	(±1.02)	(±1.88)	(±1.52)	(±1.35)	(+2.52)	(±0.35)	(±3.16)
	Forced	15.68	12.11	12.74	5.72	10.52	11.67	12.80	10.97	15.56	7.78	18.80
	Left	(±4.06)	(±3.27)	(±1.50)	(±0.89)	(±0.56)	(±0.62)	(±2.20)	(±0.50)	(±3.00)	(±1.72)	(±3.36)
Dyslexics	**Free**	9.85	12.46	10.44	11.59	9.61	8.61	8.01	8.22	9.42	9.16	8.75
		(±1.57)	(±1.98)	(±1.13)	(±1.13)	(±1.09)	(±1.11)	(±1.79)	(±2.39)	(±1.27)	(±2.66)	(±1.19)
	Forced	10.08	11.05	10.74	11.03	13.25	9.60	10.79	14.03	11.85	15.58	12.99
	Right	(±2.63)	(±1.73)	(±0.16)	(±1.74)	(±1.06)	(±2.81)	(±1.70)	(±2.54)	(±2.93)	(±2.14)	(±1.37)
	Forced	12.70	13.08	12.12	11.67	11.94	10.66	10.97	13.42	11.63	13.12	13.55
	Left	(±1.80)	(±1.46)	(±1.82)	(±2.16)	(±2.41)	(±3.45)	(±1.95)	(±1.29)	(±2.71)	(±3.11)	(±2.62)

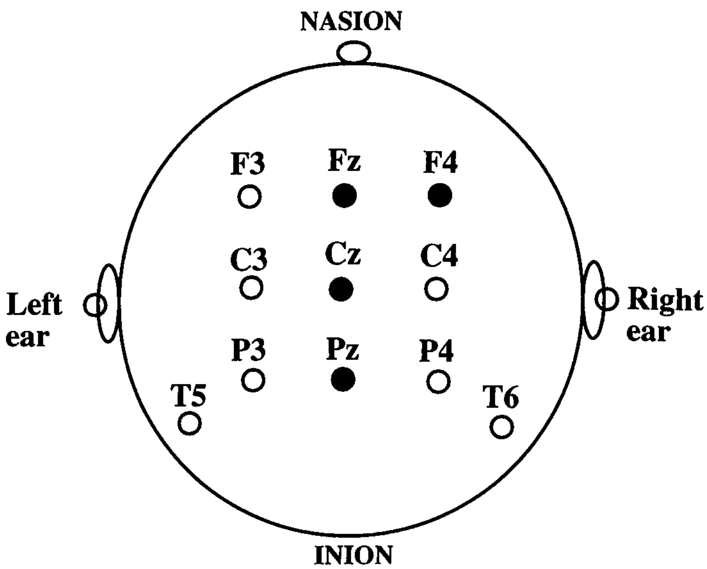
Key:
Recall: {Free - Dichotic listening free recall condition
{Forced right - Dichotic listening forced right ear recall condition
{Forced left - Dichotic listening forced left ear recall condition

Figure 7.24a. P200 ERP amplitudes recorded from the reading-age matched control readers, displaying predominantly left hemisphere activation



Key: Filled-in circles indicate the regions of maximal activation, as described in the text.

Figure 7.24b. P200 amplitudes recorded from the dyslexic readers - the only lateralised activation is seen in the frontal region of the right hemisphere



Key: Filled-in circles indicate the regions of maximal activation, as described in the text.

7.10.5 (b) ii. Topographic analyses:

Analysis of these data, with the between-group differences in level of activation controlled for, again yielded a significant interaction between cortical regional activation and reading ability group [$F(10, 160) = 1.93$; $p = 0.05$].

7.10.5. (c) Auditory -evoked potentials: latency measures:

A significant between-subjects effect of reading ability was obtained from analysis of the N100 latencies from the reading-age matched children [$F(1, 16) = 4.86$; $p = 0.04$ - see **table 7.10a**]. This effect reflected the shorter mean latencies produced by the normal readers (mean latency = 139.15 msec) than by the dyslexic children (mean latency = 155.53 msec).

A recall condition by reading group effect [$F(2, 32) = 5.99$; $p = 0.01$] emerged from these data. Overall the latencies produced by the dyslexic children in the free (mean latency = 137.92 msec) and forced right ear (mean latency = 131.91 msec) recall conditions were significantly longer than those produced by the control children (mean latencies = 117.50 and 97.77 msec respectively; both p values < 0.005). This pattern was reversed when attention was directed to the left ear ($p = 0.01$).

Analysis of the P200 latencies revealed an interaction between task condition and reading group [$F(2, 32) = 4.86$; $p = 0.03$] indicating that the dyslexics' longest latencies were elicited in the forced right ear recall condition (mean latency = 232.9 msec) whereas the controls produced their longest latencies when their attention was directed to the left ear stimuli (mean latency = 223.84 msec). In the forced right ear recall condition the latencies of the dyslexic children were significantly longer than those of the control children (**table 7.10b**); this pattern was reversed in the forced left ear recall condition (both p values < 0.005).

Table 7.10a. Mean N100 latencies (microvolts) and standard errors for the reading- age- matched children , by recall condition.

Group	Recall	F3	F4	C3	C4	P3	P4	T5	T6	Fz	Cz	Pz
Controls	**Free**	124.75	126.57	135.86	125.57	116.00	126.14	124.57	134.86	132.57	137.29	125.86
		(±12.97)	(±11.36)	(±6.03)	(±6.59)	(±12.44)	(±11.34)	(±9.24)	(±12.23)	(±18.86)	(±20.99)	(±18.16)
	Forced Right	104.88	107.11	109.44	125.56	119.56	99.75	103.00	101.89	101.67	106.13	94.22
		(±20.11)	(±15.76)	(±10.80)	(±15.75)	(±12.70)	(±12.88)	(±11.44)	(±14.06)	(±15.28)	(±15.06)	(±11.97)
	Forced Left	127.78	132.33	135.44	127.44	123.22	141.00	150.00	143.22	158.67	168.11	154.56
		(±15.93)	(±17.72)	(±17.58)	(±12.40)	(±13.47)	(±12.81)	(±13.72)	(±14.88)	(±6.96)	(±6.34)	(±7.11)
Dyslexics	**Free**	145.33	153.50	145.83	147.33	137.17	141.33	156.00	170.33	159.33	138.00	160.83
		(±8.15)	(±5.65)	(±2.34)	(±4.65)	(±10.56)	(±11.60)	(±21.48)	(±22.98)	(±5.43)	(±7.27)	(±3.94)
	Forced Right	149.00	126.50	149.60	142.80	155.80	121.80	146.20	156.80	148.40	148.00	138.00
		(±17.00)	(±29.08)	(±11.12)	(±10.77)	(±10.85)	(±20.69)	(±16.78)	(±18.29)	(±9.36)	(±11.04)	(±19.51)
	Forced Left	133.50	124.88	143.38	131.88	120.13	132.75	151.00	153.13	128.57	129.13	134.50
		(±7.44)	(±5.80)	(±3.54)	(±7.00)	(±10.94)	(±5.51)	(±16.59)	(±18.00)	(±5.00)	(±5.67)	(±5.47)

Key:
Recall: {Free - Dichotic listening free recall condition
{Forced right - Dichotic listening forced right ear recall condition
{Forced left - Dichotic listening forced left ear recall condition

Table 7.10b Mean P200 latencies (microvolts) and standard errors for the reading-age matched children , by recall condition.

Group	Recall	F3	F4	C3	C4	P3	P4	T5	T6	Fz	Cz	Pz
Controls	**Free**	209.57	214.00	231.43	244.29	247.57	222.00	257.29	235.71	221.29	229.71	219.71
		(±3.96)	(±4.21)	(±16.62)	(±6.04)	(±10.39)	(±15.61)	(±36.61)	(±14.10)	(±5.81)	(±8.79)	(±12.91)
	Forced	212.25	208.44	241.33	211.78	227.67	242.11	236.11	242.67	195.78	216.78	242.89
	Right	(±8.66)	(±7.36)	(±10.05)	(±14.94)	(±16.72)	(±16.09)	(±19.55)	(±17.15)	(±5.88)	(±12.10)	(±18.51)
	Forced	217.33	218.78	231.78	225.56	226.56	271.00	294.00	283.89	241.33	233.89	242.00
	Left	(±2.07)	(±3.13)	(±7.44)	(±6.22)	(±16.74)	(±14.92)	(±20.76)	(±17.99)	(±10.11)	(±7.10)	(±13.89)
Dyslexics	**Free**	213.83	216.17	220.67	216.83	218.00	222.17	241.00	273.33	240.67	218.00	231.00
		(±3.59)	(±7.31)	(±7.74)	(±4.87)	(±8.74)	(±9.16)	(±18.75)	(±22.04)	(±17.56)	(±6.17)	(±15.16)
	Forced	242.60	214.80	225.20	254.80	253.00	293.80	256.00	295.60	252.00	251.40	255.60
	Right	(±20.17)	(±8.37)	(±5.11)	(±30.31)	(±30.21)	(±27.43)	(±30.86)	(±22.70)	(±30.74)	(±32.03)	(±30.17)
	Forced	215.00	205.75	217.13	206.50	228.63	213.00	273.63	272.38	253.88	208.50	252.25
	Left	(±8.11)	(±12.61)	(±4.43)	(±13.05)	(±12.88)	(±25.09)	(±13.52)	(±12.80)	(±14.70)	(±10.06)	(±14.45)

Key:
Recall: {Free - Dichotic listening free recall condition
{Forced right - Dichotic listening forced right ear recall condition
{Forced left - Dichotic listening forced left ear recall condition

7.10.6. Correlational analyses I: handedness/ phonological awareness

Analysis of the hand skill and hand preference measures with the accuracy data from the phonological oddity task revealed a significant correlation between the hand preference scores and accuracy in the middle-sound-different condition [$r = -0.51$; $p = 0.03$]. This correlation indicated that greater dextral preferences are associated with increased accuracy on the phonological oddity task.

7.10.7. Correlational analyses II: AEP/ dichotic listening measures

Within the control sample significant correlations were found between left hemisphere N100 amplitude and ear advantages in the free recall condition [$r = 0.69$; $p = 0.04$] and in the forced recall conditions [$r = 0.70$; $p = 0.03$]. These correlations were positive such that increased accuracy for the reporting of dichotic stimuli perceived in the left ear was associated with larger amplitude N100s recorded from over the left hemisphere.

Analysis of the data from the dyslexic children revealed that right ear accuracy in the forced recall condition of the dichotic listening task correlated significantly with P200 amplitude in the left hemisphere; this correlation was negative [$r = -0.67$; $p = 0.05$], indicating that greater accuracy for reporting right ear dichotic stimuli was associated with lower left hemisphere amplitudes.

7.11. Discussion of results:

The aim of this second study was to expand on the results from Study 1 by controlling for the influence of reading ability on the cognitive and psychophysiological profiles of the good and poor readers. By matching the dyslexics with control children of the same reading-age it may be possible to infer the developmental course of relationships between any cognitive and cerebral anomalies observed in the dyslexic children and the reading difficulties which they experience.

7.11.1. How useful is handedness as an index of the neuropsychological substrate of competent and impaired reading?

Both samples of children in the present investigation displayed an overall bias in favour of the right hand, thus supporting the findings from Study 1 in arguing against suggestions of abnormal handedness in dyslexics. Contrary to the groups matched on the basis of their chronological-ages, however, the good and poor readers matched for reading-age differed significantly in terms of both left and right hand skill as a result of the greater overall hand skill of the dyslexic children. In view of the fact that the dyslexics in the present study were significantly older than the control children this finding is unsurprising and would appear to indicate a developmental influence over the children's hand skill in support of the findings from the longitudinal study (see **Section 6.6.1 (b)**, also Fennel *et al*, 1983; Curt *et al*, 1992).

A surprising adjunct to the results from the measure of hand skill is the finding that the dyslexic children proved significantly less right-hand preferent than the control children (as in Study 1). In view of the fact that this dyslexic sample did not include any self-professed sinistrals it would appear that the dyslexic children conform to predictions of a raised incidence of mixed handedness (Bishop, 1990; Eglinton & Annett, 1994). That a lesser degree of dextral preference was found in the dyslexic children than in either the chronological-age or the reading-age matched control children may be interpreted as indicating that rather than merely reflecting a maturational effect it is reflective of some aspect of the dyslexia - possibly related to subtle differences in the degree of underlying lateralisation; this relationship is unclear, however, on the basis of the present findings.

The possibility that handedness may be regarded as an indirect index of cerebral functional lateralisation is supported by the finding of a significant correlation between hand preference and performance on the phonological oddity task. This correlation mirrors the one obtained in the previous study in indicating that greater dextrality is associated with greater phonological processing skill. Once again it would appear, therefore, that some mechanism which favours the left hemisphere for the mediation of linguistic processing also bestows an advantage on the right hand (Annett & Manning, 1990b; Annett, 1992b).

7.11.2. How useful is the dichotic listening task as an index of the neuropsychological substrate of reading?

Verbal REAs were observed in both the good and the poor readers in the present study in support of previous studies employing the verbal dichotic listening paradigm (Kershner & Micallef, 1992; Duvelleroy-Hommet *et al*, 1995). This would indicate that the physiological mechanisms responsible for the processing of language in the left cerebral hemisphere, and thus for bestowing a perceptual advantage on the right ear, are in place in both groups of readers. These results would serve, therefore, to argue against suggestions of anomalous cerebral lateralisation in dyslexic children, at least for the perception of relatively meaningless dichotic stimuli. That this ear advantage only emerged in the forced recall conditions and not in the free recall condition may reflect the fact that directing the children's attention to the right ear serves to enhance any existing perceptual bias towards this ear (Hiscock & Kinsbourne, 1977, 1980; Boliek *et al*, 1988). The instruction to attend to both ears in the free recall condition may actually eliminate this perceptual bias. Empirical support for the absence of a verbal REA under free recall exists for both normal readers (Jancke *et al*, 1992; Duvelleroy-Hommet *et al*, 1995) and dyslexics (Witelson & Rabinowitch, 1972; Witelson, 1977; Obrzut *et al*, 1985).

Once again it is possible that the absence of significant differences in the level of accuracy achieved by the two samples may reflect a tendency towards a floor effect in the performance of the children, as previously found by Milberg *et al* (1981) and by Aylward (1984). Alternatively, it may be function of the relatively meaningless stimuli employed. As the C-V stimuli are not overtly "linguistic", it is possible that the children perceived them in the manner of nonsense sounds rather than as words, so the dyslexic children were in no way penalised in their performance on the task (Springer & Eisenson, 1977; Mercure & Warren, 1978; Obrzut, 1989).

7.11.3. What of the electrophysiological measures?

The results obtained from the reading-age matched children on the electrophysiological measures are comparable to those for the chronological-age matched samples. The control children again displayed the larger amplitude and shorter latency ERPs indicative of predominantly left hemisphere involvement (see Van de Vijver *et al*, 1984; Tenke *et al*, 1993; Ahonniska *et al*, 1993); the dyslexics showed either no lateralised activation or an apparent reversal of lateralisation (as reported by Landwehrmeyer *et al*, 1990; Segalowitz *et al*, 1992). The ERPs recorded from the dyslexic children were generally of equal amplitude bilaterally, although the P200 component was associated with a right hemisphere frontal focus which biased the activation in favour of the right hemisphere. The latencies also indicated a right hemisphere bias in that they were longest when attention was directed to the right ear; this is in contrast to the control children whose longest latencies accompanied forced left ear recall. Although these results might prompt suggestions of anomalous functional lateralisation in the dyslexic children, the verbal REA observed in the dichotic listening test would argue against this suggestion. It is again proposed, therefore, that the pattern of activation displayed by the dyslexic children may either reflect a relative inability to appropriately allocate attentional resources (as discussed in **Section 7.6.3**, see also Hugdahl & Andersson, 1987; Boliek *et al*, 1988; Obrzut, 1991) or a lesser degree of automaticity in these children in the perception of dichotically presented linguistic information (again discussed in **Section 7.6.3**; see also Goldberg & Costa, 1981; Dool *et al*, 1993).

This latter suggestion is counter-intuitive, however. As the two samples are matched on the basis of reading ability it might be expected that they would show equivalent degrees of automaticity - or lack of it - in the processing of the dichotic stimuli. This is not the case. The behavioural measures indicate that the dyslexics performed the dichotic listening task (and the phonological oddity task) with a similar level of accuracy to that displayed by the control readers. It is suggested, therefore, that whereas the reading-age matched children performed the tasks with some degree of automaticity, the difficulties experienced by the dyslexics still invoke a reliance upon the processing abilities of the right hemisphere to achieve a comparable level of accuracy (see Bakker, 1979, 1992; Dool *et al*, 1993). Once again the larger amplitude and longer latency ERPs recorded from the dyslexic children, would suggest that these children experienced a greater degree of difficulty in the processing of the dichotic stimuli than the control children (Wood, 1990; Harter *et al*, 1989; Wood *et al*, 1991).

The results of the correlational analyses offer further support to the findings of Study 1 in that increasing behavioural (right ear) accuracy of the dyslexic children on the dichotic listening task was associated with lower amplitude ERPs recorded from over the left hemisphere. As discussed in **Section 7.6.3.**, it is possible that the dyslexic children who performed with greatest accuracy on the dichotic listening task were those who needed to expend the least effort; this was reflected in their lower levels of activation in comparison with the other dyslexics (Wood, 1990; Wood *et al*, 1991). With regards to the control readers, however, greater left ear accuracy on the dichotic listening task correlated with increased amplitudes in the left hemisphere. This may suggest that these children are experiencing some difficulty in attending to stimuli in the left ear, possibly involving an attenuation of any perceptual bias which may exist towards the right ear. This greater difficulty would appear to be expressed in terms of greater amplitudes in the dominant, left, hemisphere. Alternatively, it may be that the greater left hemisphere amplitudes are the result of activation of the left hemisphere by stimuli direct from the right ear in addition to the activation produced by the processing of stimuli from the left ear in the forced left ear recall condition (Eslinger & Damasio, 1988; see also Hugdahl, 1995).

In an attempt to reconcile the apparently contradictory findings from the control and dyslexic children it is hypothesised that an optimal level of activation is required for the accurate performance of a behavioural task. Whereas this level is achieved by normal readers by increasing their activation from a base level (Harter *et al*, 1988a, b; Naylor *et al*, 1990; Hugdahl, 1995), it is possible that dyslexic children are less able to control their cerebral activation, so that they initially produce an excess of activation - a "mass response" (Bakker *et al*, 1980; see also Kershner, 1985, 1988; Kershner & Morton, 1990). This must then be attenuated to reach the optimal level (Richardson, 1995). This hypothesis may be investigated further in the study reported in **Chapter 8**.

7.11.4. Were the good and poor readers distinguishable on the basis of phonological processing ability?

Overall the two reading-age matched samples experienced significantly greater difficulty performing the alliterative awareness condition of the phonological oddity task than either of the other two (rhyming) conditions. This pattern of results was previously reported for the two groups matched on chronological-age and for the children in the longitudinal study. Possible explanations for this finding are discussed at some length in **Section 6.6.1. (c)**, so will not be reiterated here.

The two samples of children were found to perform in the first-sound-different and the last-sound-different conditions of this task with a similar level of accuracy, suggesting that the ability to distinguish between words on the basis of either their initial or their ultimate sounds is a function of the reading ability of the individual. This finding accords with the results from Study 1 in which the older control children (of the same chronological-age as the dyslexics but with a greater reading-age) were found to perform on this task with a generally higher level of aptitude than the dyslexics (see **Section 7.6.4**; also Bradley & Bryant, 1978; MacLean *et al*, 1987).

The middle-sound-different condition differentiated between the two groups, in that the younger reading-age controls attained a significantly greater level of accuracy compared with the older dyslexic children. That this difference in ability emerged in spite of the fact that the two groups were equated in terms of their literacy skills may indicate that the type of phonological processing ability required for the performance of this task is not the same as the phonological processing skills which have been implicated in the onset of literacy acquisition. The reciprocal time-lagged correlations observed between the three conditions of the phonological oddity task and the acquisition of literacy in the longitudinal study (**Section 6.5.5 (a)**) would argue against this possibility, however. Alternatively, it may be that some *tertium quid* (possibly physiological) is responsible for the impaired ability of the dyslexic children to distinguish between the sounds in this condition of the task; support for this suggestion derives from the observation that the dyslexics also tended to perform worse than the control children on the other rhyme condition (last-sound-different) of the phonological oddity task, although this difference failed to reach significance.

7.11.5. Can the two groups be discriminated on the basis of any other cognitive ability?

Surprisingly, the only other task which significantly differentiated between the good and poor readers matched on the basis of reading-age was block design. Contrary to expectations, however, it was the dyslexics who demonstrated the greater competence of the two groups on this task. In view of the finding of no significant differences in performance level between the two groups of children in Study 1 it may be inferred from these results that performance on this task is related more closely to maturational effects (chronological-age) than to literacy. This possibility receives empirical support from the finding of developmental improvements in skill on this task displayed by the children in the longitudinal study, as reported in **Section 6.6.1** (e).

Once again, as suggested in **Section 7.6.4.** for the chronological-age matched subjects, it is possible that the failure to find a significant difference in ability on the matching of letter-like forms task may be due to the fact that both groups of children performed the task near ceiling level. Both groups of children had a mean chronological-age at the upper end of the age range for which this test was designed; the high level of competence of all the children - good and poor readers - on this simple task may obscure any differential visual perceptual capabilities which may exist in the dyslexic and control samples.

The failure of the present study to find a group effect on the digit span test may be interpreted in terms of evidence relating verbal memory span to reading ability (Baddeley, 1983; Baddeley, Logie, Nimmo-Smith & Brereton, 1985). The possibility that this relationship is reflective of comparable linguistic processing abilities of the two samples (see Baddeley & Hitch, 1974; Hulme & Roodenrys, 1995) receives support from the equivalent levels of performance of the reading ability matched children on two out of the three conditions of the phonological oddity task, as discussed earlier.

The finding of similar memory capacities in the good and poor readers in spite of the chronological-age difference between the two groups may initially appear surprising considering evidence (including that reported in **Chapter 6**) of maturational effects in phonological memory (Case *et al*, 1982; Hitch & Halliday, 1983; Siegel, 1994). It should be noted, however, that although the difference in chronological-age between the two groups in the present study was statistically significant the actual mean difference was only approximately one year. Previous evidence has indicated that short-term memory capacity increases dramatically in the early school years then increases at a somewhat slower rate until adolescence from where increases are again fairly rapid, peaking at late adolescence (Siegel, 1994; Ford & Silber, 1994). This relatively small (although significant) difference in chronological-age between the two groups of children in the present study, at a developmental stage which is not characterised by particularly rapid increases in phonological memory capacity, may account for this apparent anomaly.

7.11.6. Summary of findings from Study 2:

The results from this second cross-sectional study serve to complement those from Study 1. The dyslexic readers' problems were found to exist predominantly in the domain of phonological processing although this was not reflected in the relatively simple measure of verbal memory span. The hand skill and dichotic listening measures combined to indicate that the specific processing difficulties experienced by dyslexic readers are not reflective of underlying differences in *direction* of cerebral lateralisation, although the hand preference measures may suggest that differences exist in the *degree* of lateralisation of the competent and impaired readers.

Together with the results from the indirect laterality measures the electrophysiological data appear to argue against hypotheses proposing that dyslexics' problems are the result of a maturational lag in functional organisation; the pattern of activation displayed by the dyslexic children differed not only from that of chronological-age matched normal readers but also from that of reading-age matched good readers. It is hypothesised, therefore, that the difficulties experienced by dyslexic children are a function of the information *processing* - possibly involving an inherent inability in poor readers to suppress the involvement of the non-dominant hemisphere, at least during the perception of dichotically presented verbal information - rather than with the neural *processor*.

7.11.7. Conclusions from Studies 1 and 2 and future directions:

In view of the evidence from Studies 1 and 2, it is suggested that the different literacy and cognitive processing skills of the competent readers (chronological-age and reading-age matched) and the developmental dyslexics are not the result of structural inter-hemispheric differences. Differential patterns of *inter*- and *intra*-hemispheric activation during linguistic processing certainly distinguished between the reading ability samples, however. Possible differences in the allocation of attentional resources and in the automaticity of processing strategies have been discussed.

The distinctive neuropsychological profiles of the competent and impaired readers have also been related to their cognitive profiles. Phonological discrimination skills, for example, which were exhibited with varying degrees of competence by the good and poor readers, were found to be reflected in both handedness and lateralised electrophysiological activation. Thus, the employment of these measures as indices of cerebral functional lateralisation is validated.

The hypothesis that the cognitive and literacy abilities of children are the result of differential processing styles is further explored in the third cross-sectional study (reported in **Chapter 8**). This study was designed to focus on the P300, a component of the ERP thought to reflect more cognitive, rather than sensory, aspects of processing, to elucidate the extent of the deficits experienced by dyslexic children in the processing of linguistic information.

~ CHAPTER 8 ~

Cross-sectional (P300) study:
Cognitive and psychophysiological correlates
of differential reading ability

8.1 Introduction:

The results of the previous experiments generally supported the contention that poor phonological processing skills are implicated in dyslexia but otherwise failed to detect any other cognitive impairments in the reading difficulties experienced by these children. These studies further indicated that any differences which do exist between dyslexic children and normal readers matched on the basis of either chronological-age or reading-age may not be due to differential cerebral functional lateralisation (as indexed indirectly by hand skill or performance on a dichotic listening task). The electrophysiological evidence, however, highlighted significant differences between the good and impaired readers in term of the pattern of electrical activation produced by each reading ability group during the processing of the dichotic stimuli. These differences served to further argue against hypotheses linking dyslexia with maturational anomalies in inter-hemispheric lateralisation and were instead interpreted in terms of differential processing strategies of the good and poor readers; it was suggested that the latter may be less able than the former to suppress activation in the non-dominant hemisphere, at least during the perception of dichotically presented verbal information.

Possible doubts about the validity of these findings were raised in **Sections 7.6** and **7.11**, however, by the acknowledgement that the samples of children, good and impaired readers matched for reading-age or chronological-age, were not as well matched as would have been desired. One of the aims of the present study was to overcome the limitations of the previous study by employing larger samples of good and poor readers matched more precisely on the basis of either chronological-age or reading-age. These children were administered the same cognitive test battery as given to the children in the previous studies (see **Section 7.2.2**) with the intention of testing the validity and replicability of these earlier findings.

In view of the inconsistency in the literature with regards to the lateralised processing of C-V dichotic stimuli (Kershner & Micallef, 1992; Obrzut *et al*, 1992), the present study employed a modified version of Bradley & Bryant's (1983) phonological oddity task to evoke event-related potentials in the dyslexic children and the normal readers. This task has demonstrated validity and has been reliably found to reveal differences in the processing skills of children at different levels of reading ability (as discussed at length in **Sections 2.3** and **3.2**). A modification of the phonological oddity task was employed in the present study to evoke an aspect of linguistic processing which is more closely related (than the processing of C-Vs) to that involved in reading. The particular paradigm employed was suitable for the elicitation of the P300 component of the ERP.

This ERP component was selected in the present study on the basis that it might provide a greater degree of insight into the cognitive processing impairments of dyslexic children than revealed by the previous studies. Whereas these preceding studies focused on the early sensory (N100 and P200) components of the ERP (as investigated by Sobotka & May, 1977; Symann-Louett *et al*, 1977), the P300 component of the present study is reported to be reflective of cognitive processing (Holcomb *et al*, 1985; Taylor & Keenan, 1990; Duncan *et al*, 1994).

As detailed in **Section 4.4.7**, previous studies have reported finding smaller amplitude P300s in dyslexic than in normal readers in response to linguistic stimuli presented both in the auditory and the visual modalities (Holcomb *et al*, 1985, 1986; Taylor & Keenan, 1990). These findings have been interpreted as reflecting either decreased availability of attentional resources in the dyslexic children or simply the inability to effectively allocate available resources (Cieselski, 1989, Holcomb *et al*, 1985). Differential scalp distributions of the P300 in dyslexic and normal readers have been reported (Cieselski, 1989; Taylor & Keenan, 1990; Duncan *et al*, 1994). These have been taken to reflect anomalous patterns of cerebral lateralisation in the different samples of readers, although the precise nature of these differences remains unresolved (see **Section 4.4.8**).

The aims of this study were threefold: (1) to investigate the cognitive abilities of good and poor readers (matched for chronological-age or reading-age) as indexed by behavioural measures, with the purpose of replicating the findings of the previous cross-sectional studies; (2) to investigate the electrophysiological correlates of these cognitive differences as revealed by the endogenous components of the AEP produced in response to a phonological oddball task (explicitly designed to elicit maximal differences between the dyslexic and normal readers); and (3) to attempt to relate these electrophysiological measures directly to the performance of the children on the phonological processing task. This latter aim was intended to investigate the extent to which AEPs reflect the efficacy of underlying cognitive processing.

8.2 Method:

8.2.1 Subjects:

Seventy children participated in the study. These children - 49 boys and 21 girls - were aged between 5:06 and 12:09 years (mean age = 9.19 ± 1.86 years). Within this sample 30 children had previously been identified as developmentally dyslexic and 40 children with normal reading skills were recruited as controls. Of these 30 were matched with the dyslexics on the basis of their chronological-ages, 10 were matched on the basis of their reading-ages. Although it would have been methodologically desirable to have equated the numbers of girls and boys within the samples this was not possible; the present study included all of the children who volunteered. As the investigation of possible sex differences was not an objective of this study, the unequal numbers of boys and girls was not considered to be a problem. Nonetheless, sex was entered as a covariate in all analyses.

The dyslexic sample, again recruited via the Specific Learning Difficulties Support Service, consisted of 26 boys and 4 girls aged between 8:04 and 12:02 years (mean = 9:62 years ± 1.20). Of these children 2 reported themselves to be sinistrals, 28 dextrals. Accordingly, hand preference ratings for this sample ranged between 1 and 8 (mean rating = 2.37 ± 1.54). The children's performances on the British Ability Scales word reading test showed a mean reading-age of 7.12 years (± 0.86) with a mean discrepancy of 2.50 years (± 1.21 years) between their chronological-ages and reading-ages. Verbal IQ measures (British Picture Vocabulary Scale) yielded a mean score for the sample of 102.05 (± 2.50).

One of these children demonstrated impaired hearing during the performance of the auditory P300 task. This particular child's AEP data and his results from the Bradley & Bryant P300 task were disregarded for analytical purposes, leaving a dyslexic sample of 29 children (25 boys and 4 girls) for the electrophysiological measures.

Advertisements posted via e-mail and around the campus at the University of Warwick called for children to participate in a reading research project. Respondents comprised the chronological-age matched control group. 17 dextral boy respondents and 13 dextral girl respondents aged between 7:10 and 12:09 years (mean age = 9:87 years ± 1.47) were recruited. Handedness was confirmed by subjects' hand preference ratings obtained from the Annett Hand Preference Questionnaire (Annett, 1970). Scores were between 1 and 4 with a mean rating of 2.17 (± 0.95). The mean reading-age of the sample, according to the British Ability Scales word reading test, was 11.17 years (± 1.66). This exceeded the sample's chronological-age by a mean of 1.31 years (± 1.80 years).

Reading-age matched children were recruited from two sources. Once again advertisements were posted via e-mail and letters were also sent out to parents of year 2 children in a local school. These letters asked for volunteers to take part in a study of reading development. Unfortunately the response was rather poor. 12 children were recruited and tested. While 10 of these children had reading-ages in the same range as the dyslexics, 2 had reading-ages well beyond this level and were not included in the sample. The reading-age matched children - all dextrals - were 4 girls and 6 boys with chronological-ages between 5:06 and 7:03 years (mean age = 5:87 years ± 0.63). Hand preference ratings ranged between 1 and 3 (mean = 2.20 ± 0.92). Performance of this sample on the word reading test showed that its mean reading-age was 7.55 years (+ 1.84). The reading-ages of the children exceeded their chronological-ages by a mean of 1.68 years (± 1.61).

According to parental information, the control children's scholastic performance was at an age-appropriate level. English was spoken as a first language by all of the children and none was reported to have a history of neurological or psychiatric disorders.

8.2.2 Stimuli and Apparatus:

8.2.2 (a) Indirect measures of cerebral lateralisation (hand preference and skill):

Once again the Annett (1970) hand preference questionnaire and the Annett (1970) pegboard were employed as measures of handedness (see **Chapter 5**).

8.2.2 (b) Neuropsychological measures:

These were as administered in the previous studies (see **Chapter 5** for details).

8.2.2 (c) Direct measures of cerebral lateralisation:

A modification of Bradley & Bryant's (1983) phonological oddity task was used to elicit a P300 response. This "phonological oddball" test involved the presentation of 3 blocks of words categorised on the basis of their first sounds, their middle sounds or their ultimate sounds; within each block were libraries of "rare" and "frequent" words, the former providing the "oddball" necessary for the elicitation of the P300. After hearing each word the children were required to respond, saying either "same", if the word included the specified sound, or "different" if it did not (see **Chapter 5** for details).

8.2.2 (d) Electroencephalographic measures:

AEP data were recorded from 28 tin scalp electrodes using a NeuroScience (Series III) Brain Imager, as described in **Section 5.4**.

8.3 Procedure:

The children were brought in to the psychophysiology laboratory at the University of Warwick by either one or both of their parents. Prior to the start of the testing the procedure was outlined to the child and the parents, any questions were answered, and informed parental consent was obtained. The parents were then given the option of either remaining present throughout the session - although out of sight of the child - or departing and returning after the session had ended. Most parents chose to remain in the room.

The procedure for this study was identical to that followed in the previous cross-sectional studies (see **Section 7.3** for details), except that the dichotic listening task of the previous study was replaced by the phonological oddball task (administered as described in **Chapter 5**). AEPs were recorded during the child's performance of this task. These were averaged on-line to produce single waveforms for each electrode in each stimulus condition (first-sound, middle-sound and last-sound-different), separately for the rare and frequent responses.

8.4 Data reduction:

The cognitive test battery, the handedness measures and the phonological oddball task were scored as described in **Section 5.5**. As in the previous cross-sectional studies artefact-free waveforms from a sub-set of the scalp electrodes - F3, F4, Fz, C3, C4, Cz, P3, P4, Pz, T5 and T6 (see **Appendix 10**) - were quantified. Averaged waveforms were analysed for each subject and the amplitudes and latencies of the P300 component, to the rare and frequent stimuli in each task condition, were measured. The P300 was designated by the largest positive peak between 250 and 450 msec after stimulus onset (Alexander, Polich, Bloom, Bauer, Kuperman, Rohrbaugh, Morzorati, O'Connor, Porjesz, & Begleiter, 1994).

Analysis of the behavioural data employed Pearson's Product Moment correlation coefficients and analyses of variance with repeated measures; reading ability group was entered as the between-subjects factor and sex as a co-variate (see **Section 7.4**). The electrophysiological data were analysed in two stages. Firstly ANOVAs were calculated, with reading ability group as the between-subjects factor and with cortical region (11 levels: F3, Fz, F4, C3, Cz, C4, P3, Pz, P4, T5, T6), phonological oddball task condition (3 levels: first-sound-different, middle-sound-different, last-sound-different) and stimulus type (2 levels: rare/ frequent) as within-subject factors. A subsequent wave of analyses again invoked reading ability group as the between-subjects factor but entered hemisphere (2 levels) and task condition (3 levels) as the within-subject variables. Once again significant interactions involving AEP amplitude were tested by normalising the data and re-submitting them to analysis (see **Section 7.4**).

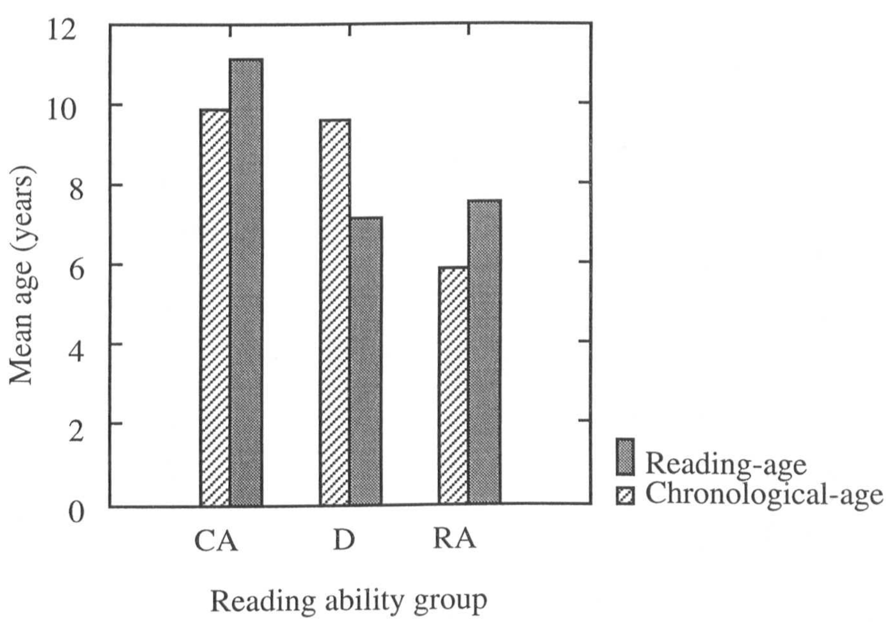
Significant results were subject to Greenhouse-Geisser conservative degrees of freedom (Greenhouse & Geisser, 1959) and Tukey's test for Honestly Significant Differences.

8.5 Results:

8.5.1. Chronological-ages, reading-ages and handedness measures

The mean chronological-ages and reading-ages of the three groups of children, along with their hand skill and preference scores are displayed in **table 8.1**. Analysis of these data revealed, as expected, a non-significant difference in chronological-age between the dyslexics and the children matched for chronological-age ($p = 0.57$) although the reading-ages of the chronological-age matched controls significantly exceeded those of the dyslexics [$F (1, 57) = 120.81$; $p < 0.005$], as displayed in **figure 8.1**. Again as expected, no difference was found between the dyslexics and the reading-age matched controls on the reading-age measure ($p = 0.35$). These two groups did differ significantly in their chronological-ages, however [$F (1, 37) = 89.20$; $p < 0.005$], with the dyslexic children the older of the two groups. The chronological-age controls were found to be older than the reading-age controls on the basis of both their chronological-ages [$F (1, 37) = 66.56$; $p < 0.005$] and their reading-ages [$F (1, 37) = 33.13$; $p < 0.005$]; see **figure 8.1**.

Figure 8.1 Mean chronological-ages and reading-ages of each group of children.



Key: CA = Chronological-age controls; D = Dyslexic children; RA = Reading-age controls.

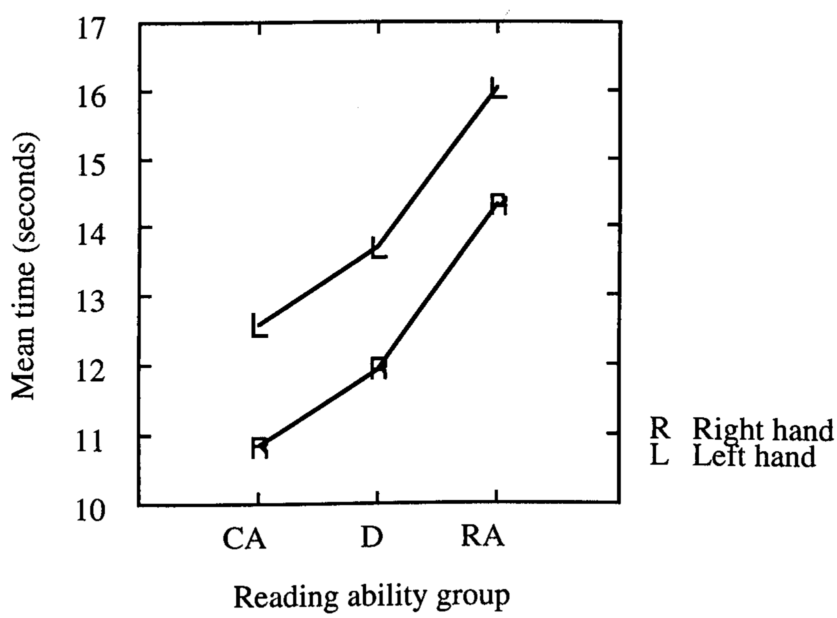
Table 8.1. Mean ages and handedness measures (with standard errors).

Reading group	**Chronological-age: years**	**Reading-age: years**	**Peg Left: seconds**	**Peg Right: seconds**	**Pegboard Laterality Indices**	**Hand Preferences**
Chronological-age controls	9.87 (±0.27)	11.17 (±0.30)	12.58 (±0.23)	10.83 (±0.17)	7.41 (±0.69)	2.17 (±0.17)
Dyslexic readers	9.62 (±0.22)	7.12 (±0.16)	13.69 (±0.33)	11.93 (±0.28)	6.83 (±0.79)	2.37 (±0.28)
Reading-age controls	5.87 (±0.20)	7.55 (±0.58)	16.02 (±0.41)	14.31 (±0.53)	5.79 (±1.31)	2.20 (±0.29)

Key: Reading-age = as determined by the British Ability Scales Word Reading test; Peg Left = left hand mean completion time on the pegboard; Peg Right = right hand mean completion time on the pegboard; Pegboard Laterality Indices = ((peg left-peg right)/(peg left+pegright)) * 100; Hand Preferences = score on the Annett Hand Preference questionnaire.

As reflected in **figure 8.2** the chronological-age matched control children were found to complete the pegboard task significantly faster than the dyslexic children with both their left hands [$F(1, 57) = 9.33$; $p < 0.005$] and their right hands [$F(1, 57) = 10.79$; $p < 0.005$]; see also **table 8.1**. The older control children also exhibited significantly greater hand skill than the reading-age matched control children with both the left hands [$F(1, 37) = 57.86$; $p < 0.005$] and right hands [$F(1, 37) = 68.80$; $p < 0.005$]. Analysis of the hand skill data from the groups matched for reading-age revealed that the dyslexics' performance significantly exceeded that of their reading-age matched counterparts for the left hand [$F(1, 37) = 11.60$; $p < 0.005$] and right hand [$F(1, 37) = 14.03$; $p < 0.005$].

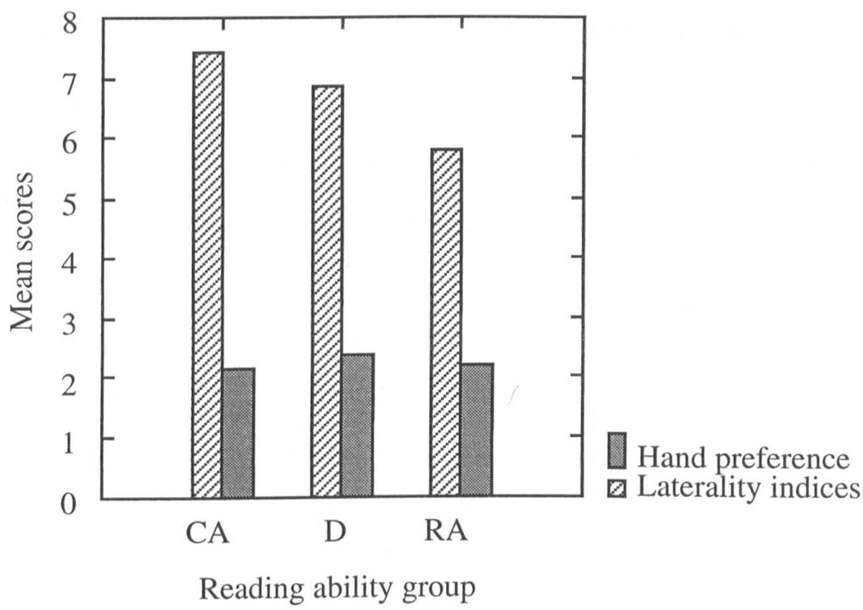
Figure 8.2. Mean completion times of the pegboard task using the left and right hands.



Key: CA = Chronological-age controls; D = Dyslexic children; RA = Reading-age controls.

A comparison of the mean task completion times yielded a significant within-subjects main effect of hand [$F(1, 66) = 62.21$; $p < 0.005$]. This reflected a right hand advantage for all three groups of children. No significant between-group differences emerged either in the hand skill laterality indices or hand preference ratings (shown in **figure 8.3**; all p values > 0.05).

Figure 8.3. Hand skill laterality indices and hand preference scores for the three reading ability groups.



Key: CA = Chronological-age controls; D = Dyslexic children; RA = Reading-age controls.

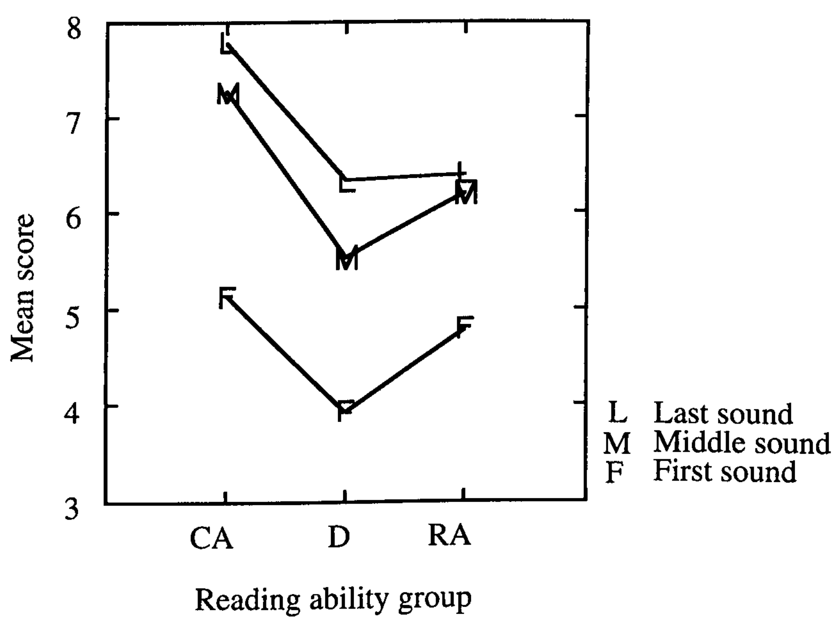
8.5.2. Psychometric measures

Analysis of the scores for the three conditions of the phonological oddity task (see **table 8.2**) yielded a main between-subjects effect of group [$F(2, 65) = 7.98$; $p < 0.005$] and a within-subjects effect of condition [$F(2, 130) = 11.54$; $p < 0.005$] - shown in **figure 8.4**. Post hoc testing of these data revealed that across the three conditions of the task the chronological-age controls displayed a higher level of accuracy than either the dyslexics ($p < 0.005$) or the younger control children ($p < 0.005$). Overall the children performed with significantly greater accuracy in the last-sound-different condition of the task than in either the middle-sound- ($p < 0.005$) or first-sound- ($p < 0.005$) different conditions, and with greater accuracy in the middle-sound than the first-sound-different condition ($p < 0.005$).

PAGE NUMBERING AS IN THE ORIGINAL THESIS

Subsequent analysis of the performance data from the first-sound-different condition of the task (see **table 8.2** and **figure 8.4**) revealed no significant differences between any of the reading groups (all p values > 0.05). Between-group differences were present in the rhyming conditions, however. These differences were found between the chronological-age controls and the dyslexics in the middle-sound-different condition [$F(1, 56) = 16.17$; $p < 0.005$] and the last-sound-different condition [$F(1, 56) = 20.24$; $p < 0.005$]. In each case the control children scored more highly than the dyslexics (illustrated in **figure 8.4**).

Figure 8.4. Mean scores achieved by each reading group in the three conditions of the phonological oddity task (out of a possible maximum of 8).

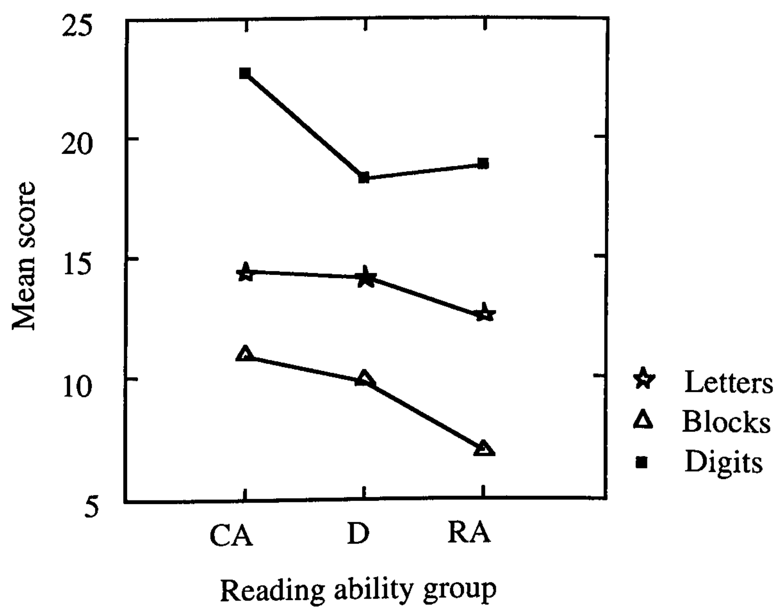


Key: CA = Chronological-age controls; D = Dyslexic children; RA = Reading-age controls.
First sound = first-sound-different condition; Middle sound = middle-sound-different condition;
Last sound = last-sound-different condition.

Differences were also found between the chronological-age matched and reading-age matched controls in the middle-sound-different [$F(1, 36) = 5.92$; $p = 0.02$] and last-sound-different [$F(1, 36) = 13.98$; $p < 0.005$] conditions (**figure 8.4**). Again these differences represented greater accuracy achieved by the older normal readers. No significant differences were found in either of these conditions between the dyslexics and the reading-age matched children (all p values > 0.05).

Significant between-group effects emerged from analysis of the digit span data (see **figure 8.5**) such that the chronological-age matched controls showed evidence of greater memory capacities then both the dyslexics [$F(1, 57) = 14.38$; $p < 0.005$] and the reading-age matched controls [$F(1, 37) = 5.36$; $p = 0.03$]; no difference was found between the two groups equated for reading ability ($p = 0.99$).

Figure 8.5. Mean scores for each group on the digit span, block design and matching of letter-like forms tasks.



Key: CA = Chronological-age controls; D = Dyslexic children; RA = Reading-age controls.
Digits = Digit recall test; Blocks = Block design test; Letters = Matching of letter-like forms test.

On the block design measure the dyslexic children scored more highly than the reading-age controls [$F(1, 37) = 5.17$; $p = 0.03$], as did the older normal readers [$F(1, 37) = 12.67$; $p < 0.005$]. The level of performance of the dyslexics and the chronological-age matched controls (shown in **figure 8.5**) did not differ significantly ($p = 0.17$).

This pattern of results is reflected in the data from the matching of letter-like forms task (**figure 8.5**). The accuracy of the two samples matched for chronological-age did not differ ($p = 0.39$) while both groups scored more highly than the younger normal readers: [$F (1, 37) = 5.12$; $p = 0.03$] and [$F (1, 37) = 11.10$; $p < 0.005$] for the dyslexic and chronological-age matched controls respectively.

8.5.3. P300 phonological oddball task I: behavioural measures

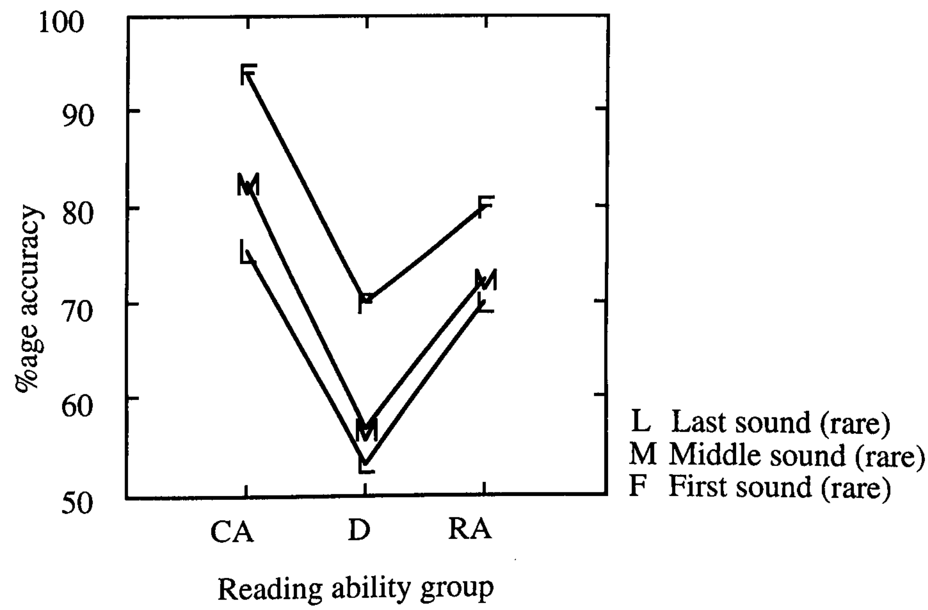
Analysis of the data from the first-sound-different condition of the phonological oddity task (see **table 8.3**) revealed that the chronological-age matched controls performed at a higher level of accuracy than the dyslexics in both the rare [$F (1, 56) = 15.43$; $p < 0.005$ - see **figure 8.6**] and frequent [$F (1, 56) = 23.43$; $p < 0.005$ - **figure 8.7**] stimulus conditions. The older normal readers were also significantly more accurate than the reading-age matched children in response to both the rare and frequent stimuli ([$F (1, 37) = 6.40$; $p = 0.02$] for the rare stimuli - shown in **figure 8.6** - and [$F (1, 37) = 8.90$; $p = 0.01$] for the frequent stimuli - see **figure 8.7**). No significant differences were found between the two groups matched for reading ability (both p values > 0.05).

Table 8.3. Mean scores (with standard errors) achieved by the control and the dyslexic children on the phonological oddball task .

Reading group	**First-sound-different: Rare**	**First-sound-different: Frequent**	**Middle-sound-different: Rare**	**Middle-sound-different: Frequent**	**Last-sound-different: Rare**	**Last-sound-different: Frequent**
Chronological-age controls	93.77 (± 1.40)	95.48 (± 1.14)	82.53 (± 4.01)	89.49 (± 2.40)	75.61 (± 4.62)	84.88 (± 1.90)
Dyslexic readers	70.06 (± 5.40)	67.60 (± 5.65)	56.71 (±4.41)	59.78 (± 5.63)	53.26 (± 4.79)	64.19 (± 4.90)
Reading-age controls	80.03 (± 8.53)	78.79 (± 9.14)	72.53 (± 7.70)	75.32 (± 7.81)	70.02 (± 9.98)	76.38 (± 6.40)

Key: First-sound-different, middle-sound-different and last-sound-different = Bryant & Bradley task conditions: Rare and Frequent stimuli.

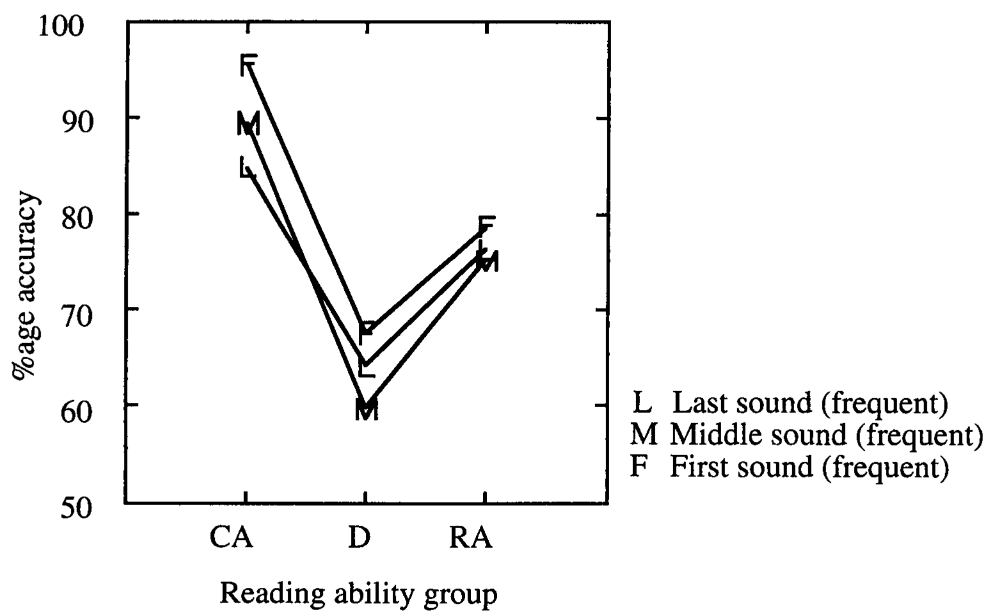
Figure 8.6. Performance of the three reading ability groups in the 'rare' conditions of the phonological oddball task



<u>Key</u>: CA = Chronological-age controls; D = Dyslexic children; RA = Reading-age controls.
First-sound = First-sound-different condition; Middle-sound = middle-sound-different condition;
Last-sound = last-sound-different condition

As in the first-sound-different condition the older normal readers were found to be more accurate in the middle-sound-different condition than were the dyslexic children (**table 8.3**). This was found for both the rare [$F(1, 56) = 17.65$; $p < 0.005$ - **figure 8.6**] and the frequent [$F(1, 56) = 20.26$; $p < 0.005$ - **figure 8.7**] stimuli. The dyslexic children were also significantly less accurate than the reading-age matched controls, but only for the rare stimuli [$F(1, 36) = 5.37$; $p = 0.03$]; no significant difference in ability emerged in response to the frequent stimuli ($p = 0.06$). The chronological-age matched controls proved significantly more accurate than the reading-age matched controls only for the frequent stimuli [$F(1, 37) = 5.65$; $p = 0.02$].

Figure 8.7. Performance of the three groups in the 'frequent' stimuli conditions



Key: CA = Chronological-age controls; D = Dyslexic children; RA = Reading-age controls.
First-sound = First-sound-different condition; Middle-sound = middle-sound-different condition;
Last-sound = last-sound-different condition

Statistical analysis of the data from the last-sound-different condition (presented in **table 8.3**) revealed significant differences in level of performance between the chronological-age matched controls and the dyslexics. The control children proved more accurate than the dyslexics in response to both the rare stimuli [F (1, 56) = 7.57; p = 0.01: **figure 8.6**] and the frequent stimuli [F (1, 56) = 13.32; p < 0.005: **figure 8.7**].

The reading-age control children also displayed significantly greater accuracy than the dyslexics at distinguishing between the rare words [F (1, 36) = 4.28; p = 0.04] but not the frequent words (p = 0.10).

Analysis of the data collapsed across reading groups revealed a significant within-subjects effect of task condition [F (2, 130) = 4.17; p = 0.02]. Accuracy in the first-sound-different condition significantly exceeded that in the middle-sound-different [F (1, 68) =

15.52; $p < 0.005$] and last-sound-different [$F (1, 68) = 27.57$; $p < 0.005$] conditions; performance levels in these latter conditions did not differ significantly ($p = 0.10$).

8.5.4. P300 phonological oddball task II: electrophysiological measures:

8.5.4 (a) P300 Amplitudes: raw waveforms:

P300 amplitudes recorded across the scalp varied for the three reading ability groups in both the rare condition [$F (20, 710) = 3.25$; $p \leq 0.005$] and the frequent condition [$F (20, 710) = 2.62$; $p \leq 0.005$] of the phonological oddball task (see **tables 8.4a** and **8.4b**). Post hoc analysis of the rare data revealed that the amplitudes recorded from the chronological-age match control children were highest across the midline and in the left hemisphere parieto-temporal regions (P3 and T5 amplitudes were larger than those from F3, C3, F4, C4, P4 and T6; all p values ≤ 0.01. See **figures 8.8** and **8.9a**); the reading-age controls similarly showed a midline and left hemisphere fronto-centro-parietal focus (F3, C3 and P3 amplitudes proved larger than those at T5, F4, C4, P4 and T6: All p values ≤ 0.005); this pattern of activation is illustrated in **figures 8.12** and **8.13a**. The dyslexic children showed a more diffuse pattern of activation in that no significant differences emerged in amplitudes recorded from homologous left and right hemisphere sites (p values > 0.05: **figures 8.10** and **8.11a**).

Further analysis of the 'frequent' data again revealed a left hemisphere parieto-temporal focus of maximal amplitudes in the chronological-age controls (see **figure 8.9b**; all p values ≤ 0.025) while, as shown in **figure 8.13b**, the reading-age controls produced their largest amplitudes generally across the left hemisphere (F3, C3, P3 and T5: p values ≤ 0.015). In contrast, the largest amplitudes produced by the dyslexic children were recorded from the left hemisphere fronto-central regions (F3, C3: p values ≤ 0.015) in addition to the midline sites (see **figure 8.11b**).

These differences resulted in significant hemisphere by reading ability group interactions, both for the rare stimuli [$F (2, 71) = 3.14$; $p = 0.05$] and the frequent stimuli [$F (2, 71) =$

3.14; $p = 0.05$]. In each instance these interactions were found to reflect greater left than right hemisphere amplitudes recorded from the control children: mean left and right hemisphere amplitudes = 15.93 μV and 11.57 μV for the chronological-age controls and 23.75 μV and 13.56 μV for the reading-age controls.

Table 8.4a. Mean P300 amplitudes (microvolts) to the rare stimuli in the phonological oddity task (with standard errors)

Group	Task	F3	F4	C3	C4	P3	P4	T5	T6	Fz	Cz	Pz
C- age	**FSD**	4.78	4.08	5.75	3.45	6.59	3.88	6.59	4.04	8.88	4.24	9.36
Controls		(±2.03)	(±1.58)	(±2.27)	(±1.90)	(±1.97)	(±2.11)	(±2.74)	(±2.08)	(±2.41)	(±1.75)	(±2.47)
	MSD	4.26	4.72	4.60	3.50	5.51	4.22	6.33	2.84	4.43	5.37	4.44
		(±1.15)	(±1.74)	(±1.39)	(±1.53)	(±2.65)	(±2.02)	(±1.91)	(±1.37)	(±1.03)	(±0.94)	(±2.14)
	LSD	1.29	2.50	4.58	2.88	6.42	5.54	7.01	4.65	3.07	6.07	7.32
		(±1.84)	(±2.20)	(±2.67)	(±2.12)	(±2.24)	(±2.82)	(±3.24)	(±2.74)	(±2.61)	(±2.75)	(±2.64)
Dyslexics	**FSD**	1.83	4.86	3.83	4.05	3.62	2.63	4.33	2.59	1.94	2.61	2.32
		(±2.07)	(±1.75)	(±2.08)	(±2.05)	(±2.40)	(±1.50)	(±2.98)	(±2.37)	(±2.49)	(±1.76)	(±2.14)
	MSD	9.47	5.09	5.73	5.70	6.34	4.08	7.64	3.85	7.42	7.25	6.88
		(±2.79)	(±2.42)	(±3.07)	(±2.45)	(±2.36)	(±3.23)	(±3.79)	(±2.13)	(±3.07)	(±2.57)	(±2.67)
	LSD	6.79	7.20	8.05	6.12	7.10	6.97	8.18	5.75	10.19	8.83	9.13
		(±2.03)	(±1.72)	(±1.78)	(±1.54)	(±2.04)	(±1.65)	(±1.74)	(±1.44)	(±1.52)	(±1.51)	(±2.16)
R- age	**FSD**	10.42	12.21	13.14	5.75	6.93	4.70	8.07	7.19	14.39	11.69	8.27
Controls		(±4.65)	(±3.55)	(±4.38)	(±1.87)	(±3.19)	(±3.98)	(±3.97)	(±5.64)	(±5.27)	(±4.57)	(±4.68)
	MSD	15.14	-2.18	-0.83	7.09	11.25	-4.32	-1.62	-8.91	-3.35	-0.13	-5.68
		(±6.75)	(±4.62)	(±5.50)	(±3.93)	(±2.85)	(±4.33)	(±8.11)	(±6.76)	(±5.90)	(±4.96)	(±8.02)
	LSD	10.09	2.78	7.40	7.71	8.71	10.38	6.31	11.86	16.19	17.57	13.10
		(±4.11)	(±4.61)	(±5.33)	(±3.25)	(±2.72)	(±3.88)	(±1.91)	(±4.66)	(±5.47)	(±4.96)	(±5.14)

Key: C-age Controls - Chronological-age matched control children; R-age Controls- Reading-age matched control children.
FSD/ MSD/ LSD- First/ Middle/ Last-sound-different condition of the phonological oddity task.

Table 8.4b. Mean P300 amplitudes (microvolts) to the frequent stimuli in the phonological oddity task (with standard errors)

Group	Task	F3	F4	C3	C4	P3	P4	T5	T6	Fz	Cz	Pz
C- age	FSD	0.56	0.74	2.39	1.46	3.82	2.10	0.61	1.33	1.88	2.13	1.62
Controls		(±0.71)	(±0.94)	(±1.30)	(±1.11)	(±1.28)	(±1.17)	(±1.35)	(±0.99)	(±1.74)	(±1.31)	(±1.27)
	MSD	2.03	-0.25	0.74	-0.57	1.79	0.89	0.30	0.80	0.12	0.90	2.40
		(±1.23)	(±0.97)	(±1.17)	(±0.89)	(±1.37)	(±1.26)	(±1.30)	(±0.62)	(±1.44)	(±0.93)	(±1.59)
	LSD	-0.13	2.40	1.48	-1.25	2.74	2.53	2.78	2.83	3.16	2.14	1.45
		(±0.89)	(±1.68)	(±1.30)	(±1.27)	(±1.74)	(±1.77)	(±1.96)	(±2.27)	(±1.92)	(±1.81)	(±1.23)
Dyslexics	FSD	2.26	2.50	2.72	2.87	2.01	2.25	1.90	0.38	2.63	3.93	2.10
		(±1.10)	(±1.14)	(±1.44)	(±1.18)	(±0.89)	(±1.36)	(±1.41)	(±1.05)	(±1.62)	(±1.03)	(±1.35)
	MSD	4.77	2.80	3.58	1.33	2.99	2.02	-0.22	-1.07	1.78	2.93	3.43
		(±1.35)	(±0.86)	(±1.28)	(±0.80)	(±1.17)	(±1.17)	(±0.88)	(±0.71)	(±1.19)	(±0.99)	(±1.14)
	LSD	2.71	0.82	1.97	0.00	2.81	2.20	2.11	1.02	3.16	2.75	2.72
		(±1.34)	(±1.26)	(±1.42)	(±1.30)	(±1.31)	(±1.51)	(±1.87)	(±1.48)	(±1.83)	(±1.41)	(±1.43)
R- age	FSD	2.39	2.22	1.42	1.92	5.08	1.88	2.54	2.87	0.61	5.07	3.40
Controls		(±1.74)	(±1.55)	(±1.76)	(±2.05)	(±1.39)	(±1.49)	(±1.67)	(±2.02)	(±2.66)	(±3.05)	(±1.93)
	MSD	4.26	-2.85	-0.52	3.38	3.23	1.28	2.88	-0.98	3.19	-1.41	0.54
		(±2.20)	(±2.95)	(±2.59)	(±2.74)	(±2.27)	(±4.68)	(±6.83)	(±2.40)	(±4.61)	(±1.80)	(±6.91)
	LSD	3.91	0.79	2.64	2.38	0.19	0.05	3.95	-0.17	1.29	0.36	0.20
		(±2.61)	(±2.95)	(±3.51)	(±2.27)	(±2.74)	(±3.33)	(±3.84)	(±4.28)	(±3.97)	(±2.96)	(±3.20)

Key: C-age Controls - Chronological-age matched control children; R-age Controls- Reading-age matched control children.
FSD/ MSD/ LSD- First/ Middle/ Last-sound-different condition of the phonological oddity task.

Figure 8.8. P300 evoked potentials recorded from a chronological-age matched control reader, averaged over the rare and frequent stimuli.

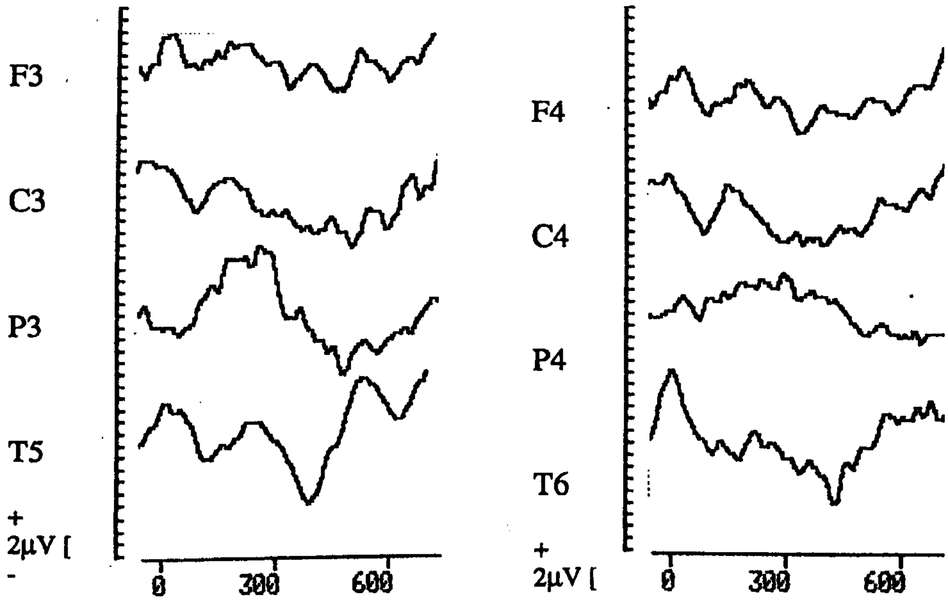
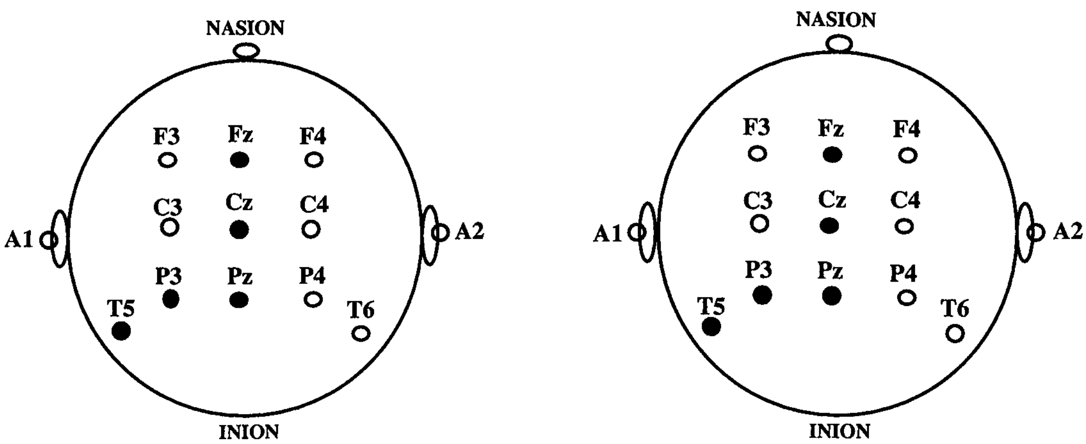


Figure 8.9a & 8.9b. P300 amplitudes recorded from the chronological-age control children in the "rare" and "frequent" conditions - each showing a left hemisphere parieto-temporal focus of activation.



Key: Filled-in circles indicate the regions of maximal activation, as described in the text.

Figure 8.10. P300 evoked potentials recorded from a dyslexic reader during the phonological oddball task

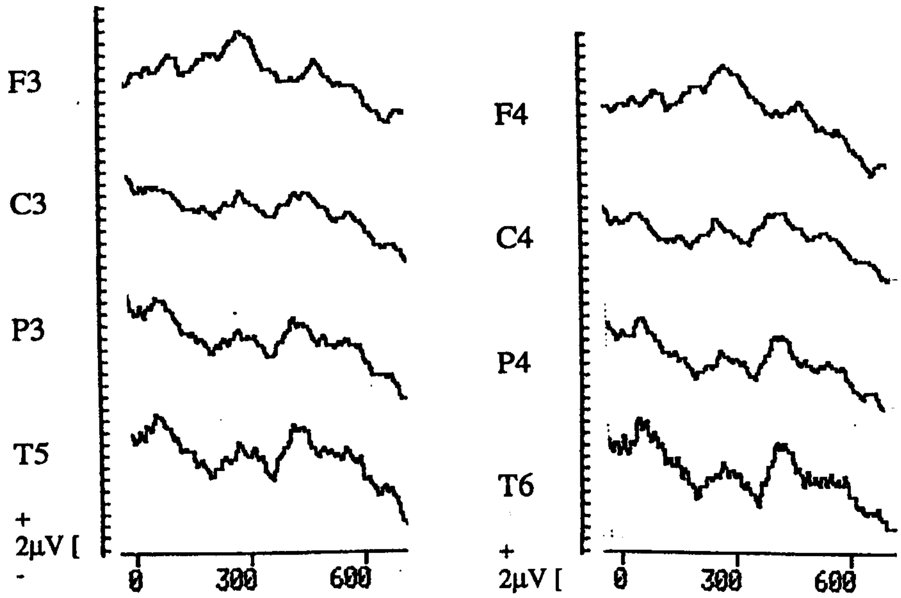
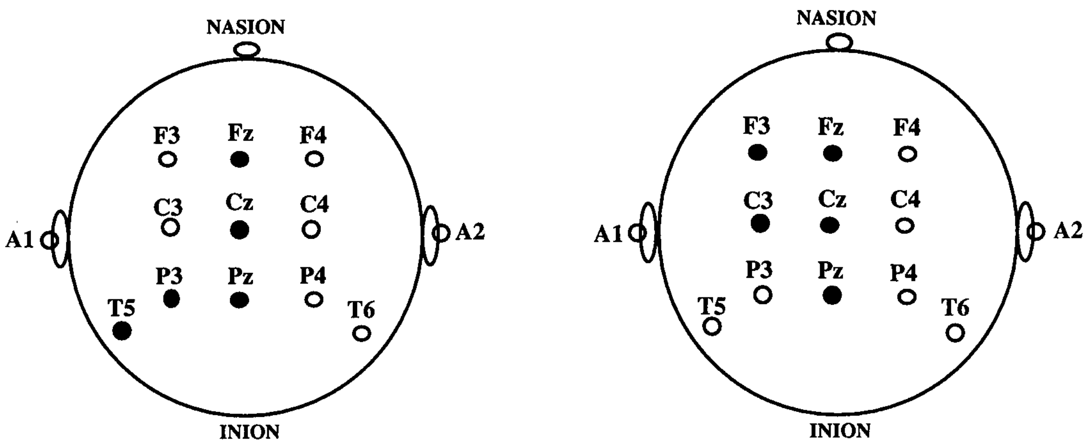


Figure 8.11a & 8.11b. P300 amplitudes recorded from the dyslexic readers in the "rare" and "frequent" conditions - no lateralised activation is seen in the rare condition; in the frequent condition activation is seen in the left hemisphere fronto-central regions



Key: Filled-in circles indicate the regions of maximal activation, as described in the text.

Figure 8.12. P300 evoked potentials recorded from a reading-age matched control child during the performance of the phonological oddball task (averaged over conditions)

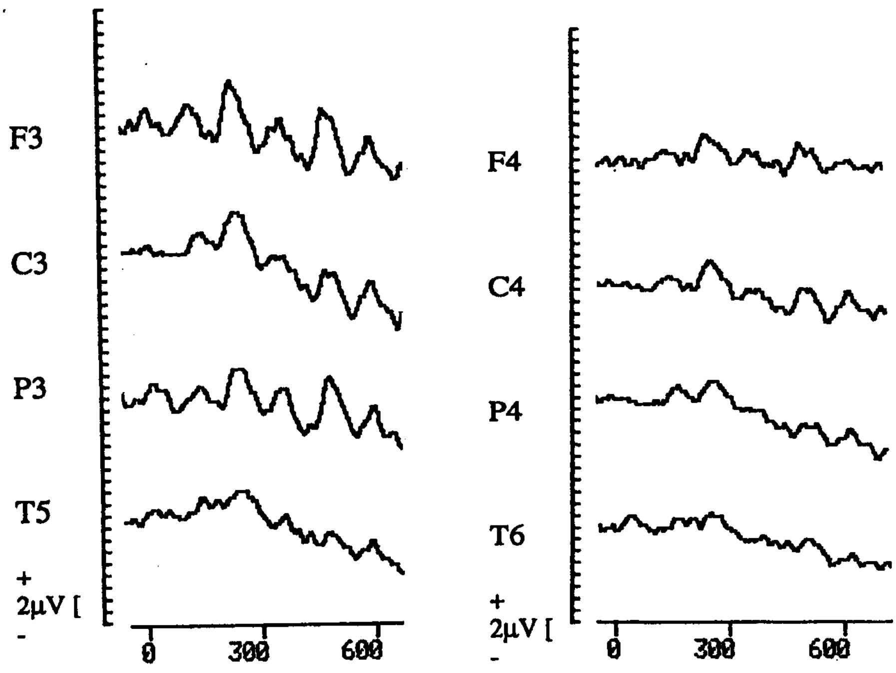
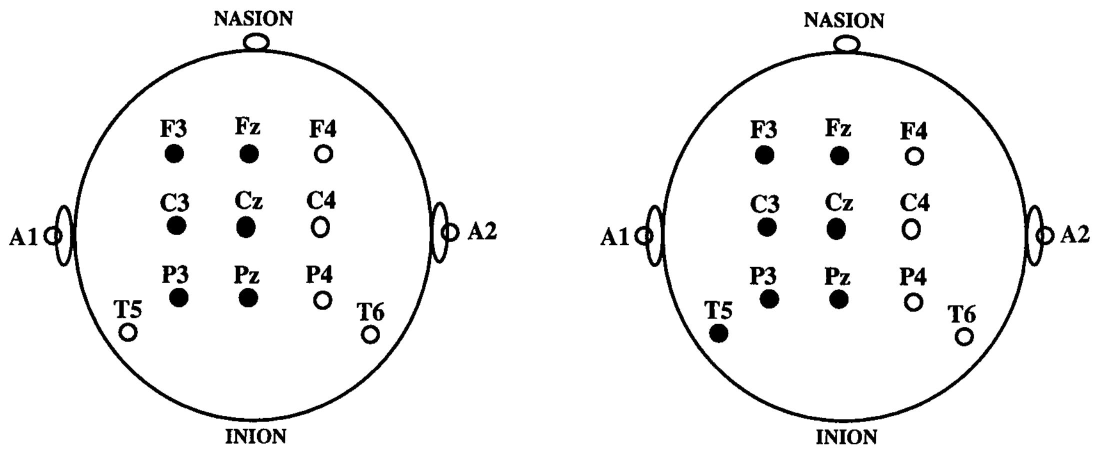


Figure 8.13a and 8.13b. P300 amplitudes recorded from the reading-age control children in the "rare" and "frequent" conditions - each showing left hemisphere lateralised activation



Key: Filled-in circles indicate the regions of maximal activation, as described in the text.

8.5.4 (b) P300 Amplitudes: topographic analyses:

Analysis of the re-scaled 'frequent' amplitude data again yielded a significant group by cortical region interaction [$F(20, 710) = 2.15$; $p = 0.01$], reflecting the previously reported left hemisphere activation in the control children which was absent in the dyslexics. Analysis of the corresponding AEP data recorded in response to the rare stimuli marginally failed to differentiate significantly between the reading ability groups ($p = 0.06$).

8.5.4 (c) P300 latencies:

Analysis of the P300 latency data, presented in **tables 8.5a** and **8.5b**, revealed a significant interaction between hemisphere and reading ability group membership in response to the rare stimuli [$F(2, 71) = 5.83$; $p \leq 0.005$]; longer latency AEPs were recorded from the right hemisphere than from the left of both groups of control children. No significant latency differences emerged from the dyslexics' data.

A significant main effect of reading ability group [$F(2, 71) = 3.20$; $p = 0.05$] emerged from analysis of the frequent data such that the dyslexic children produced longer latency AEPs than the chronological-age match children, while the reading-age match controls produced the longest latencies of the three groups (all p values ≤ 0.005). A hemisphere by group interaction [$F(2, 71) = 3.13$; $p = 0.05$] revealed that the latencies recorded from the left hemispheres of the chronological-age (mean = 344.85 msecs) and reading-age (mean = 367.16 msecs) controls were shorter than those recorded from the right hemispheres (means = 346.36 msecs and 372.71 msecs respectively for the two groups). No such differences were found in the left (mean = 363.94 msecs) and right (mean = 363.67 msecs) hemisphere latencies recorded from the dyslexic children.

Table 8.5a. Mean P300 latencies (milliseconds) to the rare stimuli in the phonological oddity task (with standard errors)

Group	Task	F3	F4	C3	C4	P3	P4	T5	T6	Fz	Cz	Pz
C- age	**FSD**	360.91	365.41	361.55	356.41	362.77	361.05	371.59	368.36	363.14	357.59	356.00
Controls		(±12.26)	(±12.37)	(±10.51)	(±10.68)	(±11.09)	(±10.83)	(±9.93)	(±10.74)	(±10.90)	(±11.95)	(±11.71)
	MSD	323.55	337.60	343.84	331.11	342.95	351.90	340.43	347.10	337.90	334.65	336.70
		(±11.30)	(±11.55)	(±10.95)	(±11.96)	(±13.30)	(±13.97)	(±9.92)	(±11.86)	(±11.01)	(±10.90)	(±9.16)
	LSD	365.50	354.28	364.11	348.33	380.72	389.59	375.22	376.67	375.59	386.89	372.67
		(±15.57)	(±15.51)	(±11.56)	(±16.15)	(±11.61)	(±14.08)	(±12.99)	(±17.06)	(±15.27)	(±17.11)	(±14.80)
Dyslexics	**FSD**	347.12	343.37	340.19	342.78	345.67	346.93	350.78	346.27	347.04	348.85	345.78
		(±7.83)	(±7.54)	(±7.00)	(±7.74)	(±6.52)	(±7.84)	(±8.43)	(±8.00)	(±7.16)	(±7.40)	(±7.13)
	MSD	345.38	348.76	349.00	343.36	348.04	349.96	350.04	350.36	346.12	341.88	339.96
		(±8.52)	(±8.51)	(±7.66)	(±9.17)	(±7.91)	(±9.90)	(±7.42)	(±10.72)	(±8.73)	(±7.97)	(±8.65)
	LSD	343.12	336.69	341.52	344.12	343.54	342.31	350.46	344.12	347.36	344.77	347.50
		(±7.57)	(±8.42)	(±8.24)	(±7.55)	(±8.08)	(±8.69)	(±8.21)	(±6.83)	(±8.07)	(±9.14)	(±8.20)
R- age	**FSD**	322.00	324.50	325.30	318.50	316.40	310.20	345.00	334.50	329.90	317.44	317.20
Controls		(±10.29)	(±11.64)	(±9.45)	(±10.07)	(±13.01)	(±13.66)	(±7.20)	(±9.71)	(±11.00)	(±12.41)	(±10.32)
	MSD	350.86	375.57	348.29	366.86	342.71	374	368.43	362.71	353.57	359.57	354.86
		(±22.01)	(±12.31)	(±19.18)	(±19.17)	(±24.41)	(±11.62)	(±20.51)	(±22.44)	(±17.30)	(±17.50)	(±16.09)
	LSD	339.38	356.67	359.33	372.56	345.00	379.56	357.67	366.22	361.11	368.67	364.78
		(±16.60)	(±16.51)	(±22.45)	(±20.79)	(±22.94)	(±23.67)	(±23.12)	(±20.25)	(±21.02)	(±21.84)	(±26.08)

Key: C-age Controls - Chronological-age matched control children; R-age Controls- Reading-age matched control children.
FSD/ MSD/ LSD- First/ Middle/ Last-sound-different condition of the phonological oddity task.

Table 8.5b. Mean P300 latencies (milliseconds) to the frequent stimuli in the phonological oddity task (with standard errors)

Group	Task	F3	F4	C3	C4	P3	P4	T5	T6	Fz	Cz	Pz
C- age	**FSD**	338.55	336.87	346.30	340.83	342.48	344.35	346.39	354.32	339.43	347.52	338.70
Controls		(±11.10)	(±9.78)	(±11.73)	(±11.61)	(±10.81)	(±11.16)	(±11.21)	(±13.49)	(±12.48)	(±11.37)	(±12.30)
	MSD	348.90	347.65	337.76	333.57	349.95	342.75	353.95	343.47	355.95	353.40	358.85
		(±11.78)	(±10.61)	(±10.36)	(±11.15)	(±12.40)	(±13.78)	(±11.78)	(±13.78)	(±13.08)	(±11.87)	(±14.50)
	LSD	339.35	343.88	347.39	349.61	347.33	349.17	357.94	351.76	353.81	345.72	348.56
		(±7.23)	(±9.71)	(±9.34)	(±8.77)	(±10.32)	(±7.94)	(±8.48)	(±12.16)	(±9.67)	(±8.31)	(±9.96)
Dyslexics	**FSD**	363.22	358.22	361.19	362.63	361.44	370.11	374.56	378.19	365.41	366.26	360.74
		(±12.41)	(±12.45)	(±11.99)	(±12.64)	(±11.18)	(±12.31)	(±12.79)	(±11.61)	(±13.10)	(±11.47)	(±11.88)
	MSD	360.64	352.50	354.20	349.28	357.64	351.92	361.36	365.80	358.28	363.04	357.20
		(±13.50)	(±13.43)	(±13.95)	(±13.59)	(±14.03)	(±13.04)	(±14.25)	(±13.46)	(±12.72)	(±13.94)	(±13.77)
	LSD	365.77	362.35	364.27	364.73	371.15	371.96	371.85	376.31	369.17	366.27	369.88
		(±12.92)	(±12.08)	(±12.64)	(±12.58)	(±12.11)	(±14.55)	(±14.78)	(±15.14)	(±12.46)	(±13.13)	(±14.34)
R- age	**FSD**	370.50	391.33	379.60	388.40	385.20	388.80	397.70	410.60	383.40	386.67	387.40
Controls		(±25.31)	(±24.58)	(±22.46)	(±19.07)	(±19.98)	(±20.03)	(±23.28)	(±21.61)	(±22.90)	(±23.99)	(±19.82)
	MSD	342.29	335.14	352.00	352.14	350.00	351.14	340.50	353.71	370.00	358.86	364.57
		(±16.70)	(±16.51)	(±24.53)	(±24.03)	(±27.69)	(±27.07)	(±16.04)	(±22.36)	(±27.15)	(±29.69)	(±28.70)
	LSD	356.89	371.67	368.22	356.67	381.89	391.11	381.11	381.78	368.00	378.78	369.78
		(±21.24)	(±15.12)	(±16.92)	(±22.05)	(±12.53)	(±19.25)	(±18.66)	(±16.88)	(±19.97)	(±17.31)	(±16.73)

Key: C-age Controls - Chronological-age matched control children; R-age Controls- Reading-age matched control children.
FSD/ MSD/ LSD- First/ Middle/ Last-sound-different condition of the phonological oddity task.

8.5.5. Correlational analyses I: phonological oddity/ phonological oddball task performance

Results of the phonological oddball task were correlated with the data from Bradley & Bryant's (1983) phonological oddity task to establish that the two were tapping the same constructs. These analyses revealed significant positive correlations between total accuracy on the phonological *oddity* task (over all three conditions) and total performance on the phonological *oddball* task ($r = 0.41$; $p < 0.005$). Further analyses, comparing performance *within* each condition of the two tasks (focusing on the first, middle or last sounds) yielded significant correlations between accuracy on each in the middle-sound ($r = 0.33$; $p < 0.005$) and last-sound ($r = 0.39$; $p < 0.005$) different conditions. Accuracy in the first-sound-different conditions of the two failed to correlate significantly ($p = 0.11$).

8.5.6. Correlational analyses II: handedness/ phonological awareness

No significant correlations emerged from these analyses, although the correlation between hand skill and accuracy in the alliterative awareness condition of the phonological oddity task only marginally missed significance ($p = 0.06$).

8.5.7. Correlational analyses III: AEP/ dichotic listening measures

Analysis of the data from the dyslexic children revealed significant correlations between performance in the middle-sound-different (*rare* stimuli) condition of the phonological oddball task and ERP amplitudes recorded contemporaneously. These correlations indicated that greater accuracy on this phonological oddball task was associated with *lower* amplitudes over the left ($r = -0.37$; $p = 0.04$) and right ($r = -0.38$; $p = 0.04$) cerebral hemispheres. Greater accuracy of report of the *frequent* stimuli within this condition was associated with *greater* ERP amplitudes recorded from the left hemisphere ($r = 0.42$; $p = 0.02$). A single significant correlation emerged from analysis of the data from the reading-age control children. Greater accuracy in the last-sound-different (frequent) condition correlated with reduced amplitudes from the left hemisphere ($r = -0.74$; $p = 0.04$). No significant effects were found for the chronological-age control readers.

8.6 Discussion of results:

This cross-sectional study was undertaken with the aims of investigating: (1) the cognitive processing abilities of dyslexic children and competent readers (matched on the basis of their chronological-ages or reading-ages); (2) underlying cortical asymmetries as indexed by measures of handedness and ERPs, and (3) the extent to which these electrophysiological measures reflect behavioural performance on the phonological oddball task. These aims will be considered in turn over the ensuing sections.

8.6.1. Did the dyslexics differ from the chronological-age and reading-age control children on the cognitive tasks?

*8. 6.1 (a) Phonological **oddity** task performance in relation to reading ability*

Performance on the phonological oddity task in the present study was comparable with that observed in the previous studies. Accuracy across the three groups of children was significantly greater in the rhyming (middle- and last-sound-different) conditions than in the alliteration (first-sound-different) condition. Explanations for this finding have been proposed and discussed in **Section 6.6.1 (c)**. Across the three task conditions the chronological-age control children correctly identified the odd-words-out with greater accuracy than the dyslexics and the reading-age control children. As the single most important variable which distinguishes these children from the other two samples is their reading ability, these results indicate that phonological processing skills are inextricably linked with literacy, whether as a pre-cursor or as a by-product. Of course, this relationship is almost universally accepted in the literature (Bishop & Adams, 1990; Goswami & Bryant, 1990; Gough *et al*, 1992) and has been discussed at some length through the course of this thesis.

This finding of greater phonological processing ability in the chronological-age controls *across* the three task conditions is again found by examining the data *within* each condition. These control children scored more highly than the dyslexics, of the same chronological-age, in the two rhyming conditions of the phonological oddity task. This finding again attests to the relationship between literacy and phonological awareness (see also MacLean *et al*, 1987; Fox, 1994) although, perhaps surprisingly, no significant between-group difference emerged in performance of the alliteration condition. These results support those from the previous cross-sectional studies and serve to demonstrate the reliability of the phonological oddity task as a measure of the differential phonological processing capabilities of competent and impaired readers.

Considering the data from the two samples of children matched for reading-age it is seen that no differences emerged between the two samples in their ability to differentiate between words on the basis of their middle or last sounds. This again supports the hypothesised link between phonological awareness and reading ability; similar results are reported in the literature (Vellutino & Scanlon, 1987; Johnston *et al*, 1987; Fox, 1994). As with the children matched for chronological-age, however, no significant difference was found in accuracy in this instance in the first-sound-different condition although the reading-age control children (and also the chronological-age controls) *tended* to out-perform the dyslexics. It is possible, as discussed in **Section 7.6.4**, that this failure to find any significant between-group differences in the data from the alliterative awareness condition may be a function of the generally poor performances in this particular condition; the observed difference may have been significant had greater numbers of trials been included in each task condition.

As mentioned previously these data, taken together, underscore the strength of the relationship between phonological awareness and literacy. The two groups of children equated for reading ability showed equivalent phonological skills although both groups demonstrated poorer phonological processing abilities than the control children with the superior literacy skills. These data reveal nothing about the direction of causality underlying this relationship, however, thus leaving unanswered the questions: are the equivalent phonological processing skills of the reading-age matched normal and poor readers responsible for their equivalent reading skills, or do their comparable reading abilities underlie their similar phonological processing abilities? Are the chronological-age controls' superior reading skills responsible for their better phonological processing skills or do the latter account for the former? These possibilities are discussed further in **Chapter 9**.

*8.6.1 (b) Phonological **oddball** task performance in the three reading ability groups*

The performance of the three reading ability samples on the phonological oddball task serves to support the contention that phonological processing ability is a function of the individual's reading ability. In line with the results from the previously reported phonological *oddity* task the results of the phonological *oddball* task indicate that the chronological-age control children performed with greater accuracy in all three conditions (first-, middle- and last-sound-different, both rare and frequent stimuli) than the dyslexic children of the same chronological-age. Unfortunately, as highlighted above, these results reveal nothing about the specific nature of this relationship; whether impaired reading skills inhibit the development of phonological awareness skills, for example, or whether poor phonological awareness skills impede the acquisition of reading skills. Clarification of this issue may be provided by the results of the comparison between the samples matched for reading ability.

These latter analyses indicated that in the first-sound-different condition the two samples performed at an equivalent level of competence. In combination with the finding that the older control children also out-performed the younger control children in this condition (rare and frequent stimuli) this would indicate that alliterative awareness may be more closely related to reading development than to maturational effects. Whether this relationship is causal - and if so, in which direction - or whether it is reciprocal, is unclear from these data. The longitudinal data, however, have previously been found to indicate that alliterative awareness facilitates early reading acquisition but that the relationship between the two constructs is reciprocal thereafter through the early stages of reading development.

The performance of the reading-age matched samples in the two rhyming conditions of the oddball task showed that whereas the controls out-performed the dyslexics when presented with the rare stimuli, the performance of the two samples of children was equated in response to the frequent stimuli in both conditions. Thus it would appear that the dyslexic children's phonological impairments may have little influence over their ability to distinguish between words when the common sound is presented frequently. When the children are presented with an unexpected rare (oddball) word, however, they appear to experience an inappropriately high level of difficulty in detecting this word and in identifying it as different to the frequent words amongst which it is presented. This finding may be interpreted as reflecting a deficit in stimulus categorisation in the dyslexic children (as reported by Lubar *et al*, 1990; Nicolson & Fawcett, 1994; Fawcett *et al*, 1993). The auditory oddball paradigm is based on the process of stimulus matching. To perform the task the individual must compare each perceived stimulus against a 'template' provided by the experimenter; the response of the subject depends upon whether or not the two match (Lubar *et al*, 1990; Dool *et al*, 1993; Polich, 1995). Impaired stimulus evaluation abilities would reduce the dyslexics' ability to discriminate between stimuli and to identify the auditory oddballs. This is reported in the literature for both verbal and non-verbal stimuli (Fawcett *et al*, 1993; Foale *et al*, 1995; Watkins, Baldeweg, Richardson & Gruzelier, 1995).

Of some surprise, in view of the results from the phonological oddity task reported in **Section 8.5.2** and in the previous cross-sectional and longitudinal studies, is the observation that all three samples of children performed the phonological oddball task with greater accuracy in the first-sound-different condition than in either of the rhyming conditions. This disparity is reflected in the results of the correlational analyses which indicated significant correlations between accuracy in the oddball and oddity tasks in the two rhyming conditions, but a non-significant correlation between the two measures in the first-sound-different condition. These results would appear, therefore, to validate the use of the phonological oddball task for the assessment of rhyme awareness, but they suggest that the first-sound-different conditions may be tapping different constructs, possibly reflecting subtle differences in the nature of the tasks employed in each instance. The phonological *oddity* task requires the children to remember the four words presented in each trial, determine which sound the words share and identify on this basis the word which does not share this sound. The phonological *oddball* task, in contrast, merely requires the child to remember which component of the words (first-, middle- or last-sound) they are to attend to and to evaluate the individual stimuli accordingly as they are perceived. Furthermore, whereas the children must generate templates for the performance of the oddity task on the basis of three words, in the oddball task the frequent repetitions of the "same" sounding words enables the establishment of enduring comparative templates. Thus, this latter task is the easier of the two, making fewer cognitive demands of the child (Wagner & Torgesen, 1987; Baddeley, 1990); the alliteration condition of the task merely requires simple perceptual discriminations of the first sounds of the words at the level of the rime without the need to process the word at any deeper level, as is required for the rhyming conditions (Stuart, 1990; Goswami, 1990).

8.6.1 (c) Memory capacity and reading skill

The digit span data reflect those from the phonological awareness task in their differentiation between the samples. The chronological-age matched controls demonstrated the greater memory spans relative to both the dyslexics and the reading-age control children. In the light of the relationship between phonological manipulation skills and the ability to retain information in verbal memory (discussed in **Section 2.4**), this finding may again indirectly reflect the superior phonological processing skills of the older normal readers. This finding would support the results of the previous section (also of Siegel & Linder, 1984; Hulme, 1988; Rapala & Brady, 1990). The absence of differential memory capacities between the samples with equivalent reading skills serves to underscore the relationship between phonological processing skills, reading ability and verbal memory capacity (Johnston *et al*, 1987; Thomson, 1988; Gathercole *et al*, 1991), as discussed in **Sections 2.4.2** and **3.3**).

8.6.1 (d) Visual skills and reading competence

Both the block design and the matching of letter-like forms tasks elicited equivalent performances from the two samples of children equated for chronological-age; this suggests that the differences in reading ability between these children may not be attributed to differences in visual perceptual skills, at least as measured by these relatively simple tasks. In view of the finding that both the chronological-age control children and the dyslexics scored more highly, i.e. demonstrated greater visual skill, on these two measures than the younger normal readers, it is proposed that visual ability may be primarily a function of general intellectual maturation. This suggestion, in fact, accords with the results from the longitudinal study reported and discussed in **Chapter 6**. Any extant relationship between visual skills and literary competence may either be at a more fundamental - i.e. lower - level than that tapped by these particular tests (see, for example, Livingstone *et al*, 1991; Stein, 1991; Cornelissen *et al*, 1991, 1992), or it may be that visual skills are only of influence in the initial stages of reading acquisition. This latter suggestion accords with the stage models of reading acquisition discussed in **Section 2.2** (for example, Marsh *et al*, 1981; Seymour & MacGregor, 1984; Frith, 1985) and receives support from the partialled time-lag correlations presented in the longitudinal study of the present thesis (**Section 6.5.5**).

8.6.2. Were the good and poor readers distinguishable on the basis of their cortical lateralisation?

8.6.2 (a) Handedness as an index of hemispheric lateralisation

In line with the previously reported cross-sectional and longitudinal studies all three samples of children in the present study displayed a right hand advantage for the performance of the pegboard task, and no differences were found in the hand skill laterality indices of the three samples (as reported by Rutter, 1978; Annett & Kilshaw, 1984). Once again, to the extent that a measure of hand skill may be taken as reflecting underlying hemispheric lateralisation, this finding would appear to refute suggestions that dyslexics are anomalously lateralised compared with normal readers (see also Keefe & Swinney, 1979; Rudel, 1985). Of course, it is also possible that any differences which may exist between good and poor readers in terms of cerebral lateralisation are not detectable by measures of handedness.

Also as reported previously, the dyslexic children were found in this study to perform the pegboard task significantly faster with both hands than the younger children of the same reading-age (see also Kilshaw & Annett, 1983; Fennel *et al*, 1983; Curt *et al*, 1992). Maturational effects of hand skill have been discussed in **Section 6.6.1 (b)**. In surprising contrast to the results from the previous cross-sectional study (Study 1), however, the pegboard task in the present study elicited significantly different levels of hand skill (both left and right hands) between the good and poor readers matched on the basis of chronological-age; greater overall skill was displayed by the good readers (as Moore *et al*, 1995). As these two groups of children were equated for chronological-age explanations for this finding based on maturational effects are precluded. Furthermore, the fact that the two samples differed in both left *and* right hand skill would appear to indicate that whatever mechanism is responsible for this effect in the dyslexic children is exerted bilaterally, to produce a generalised impairment manifested in impaired motoric skill. This issue is discussed further in **Section 9.5**.

In the light of the results from the previous cross-sectional studies (and also Naidoo, 1972; Annett & Turner, 1974), it is of some surprise that no significant differences emerged between the three reading ability groups in terms of hand preference. This finding *does* accord with the present results from the hand skill measure, however, in suggesting that any physiological differences which may exist between good and poor readers are poorly reflected by these simple measures of handedness. Once again, Eglinton and Annett's (1994) caution, concerning the reduced likelihood of observing "atypical handedness" in relatively small samples of dyslexics, is accepted.

While the handedness measures in this instance failed to differentiate between the competent and impaired readers, they *may* still reflect underlying functional lateralisation, to some extent; the correlation between hand skill and phonological processing ability only marginally missed significance. This lack of correlation between these two measures is surprising in the light of previous evidence (Annett & Manning, 1990b; Annett, 1992a; Brunswick & Rippon, 1994), and the reason for it is not apparent.

8.6.2 (b) Electrophysiological measures of hemispheric lateralisation

Anomalous patterns of activation were observed in the sample of dyslexic children when compared with the chronological-age and reading-age matched control children. Both samples of control children produced predominantly left hemisphere activation during the processing of the rare and frequent stimuli. This focus of activation was indicated by larger amplitudes and shorter latencies recorded from the left hemisphere brain regions than from the corresponding regions in the right hemisphere and is typical of the activation seen during the processing of verbal information (Obrzut, 1989; Tenke *et al*, 1993; Ahonniska *et al*, 1993).

Also of interest to the present study is the precise focus of activation within the left hemispheres of the two samples of normal readers. Whereas the activation in the younger control children was generally diffused across the left hemisphere the focal activation in the brains of the older control children was in the temporo-parietal regions - i.e. the classical language areas (Wood *et al*, 1991; Flowers, Wood & Naylor, 1991; Ahonniska *et al*, 1993). These data accord with hypotheses of the dynamic progression of lateralised function (Luria, 1973; Satz *et al*, 1990) which propose that physiological maturation is reflected in an intra-hemispheric progressive increase in anterior-posterior lateralisation (Satz *et al*, 1990; Satz, 1991; Boliek & Obrzut, 1995).

The activation in the brains of the dyslexic children, in contrast, failed to show the pattern of lateralisation seen in the chronological-age matched control children, as reported in the previous cross-sectional studies, and by others (Landwehrmeyer *et al*, 1990; Segalowitz *et al*, 1992; Brunswick & Rippon, 1994). Some focal activity was seen, however, in the fronto-central regions of the dyslexic brains, during the processing of the rare stimuli, producing a pattern of activation similar to that observed in the younger, reading-age, control children. It is possible that these similarities may be interpreted as reflecting an immature pattern of intra-hemispheric functional lateralisation in the dyslexic children as described above (Boliek & Obrzut, 1995). Further support for suggestions of some degree of physiological immaturity in the brains of the dyslexic children derives from the behavioural data which indicated similarities in the levels of performance of the dyslexics and the reading-age controls on the phonological oddball task (see below). Subtle differences were observed between these two samples in the electrophysiological results, however. While the good and poor readers both showed evidence of fronto-central activation, in the young good readers this was lateralised to the left hemisphere whereas in the dyslexics it was observed over both hemispheres. Bilateral frontal activation has been observed previously in reading impaired children during linguistic processing (Duffy, Denckla, Bartels, Sandini, & Kiessling, 1980; Harter *et al*, 1988a, b) and has been interpreted as reflecting 'compensatory' mechanisms in the dyslexic readers to offset left hemisphere processing inefficiency (Harter *et al*, 1988a, b; Naylor *et al*, 1990). This issue was discussed in **Chapter 4**.

8.6.3. Electrophysiological activation as an index of phonological oddball task performance:

As reported above, the performance levels of the reading-age matched good and poor readers were comparable when the children were required to process the frequent stimuli, in all three oddball conditions. The electrophysiological data recorded during this processing also showed similar patterns of activation in the two groups. The control readers displayed lateralised activation across the left hemisphere while the dyslexics exhibited their only signs of lateralisation in the fronto-central regions of the left hemisphere. During the processing of the more difficult, rare, stimuli, however, the accuracy of the younger children actually exceeded that of the older impaired readers (in the middle- and last-sound-different conditions) and the electrophysiological data indicate that no lateralised effects were produced by the poor readers during this processing. A comparison of the data from the chronological-age matched competent and impaired readers (Study 1) revealed significant behavioural and electrophysiological differences between the two. Not only did the control children outscore the dyslexics in all three conditions (rare and frequent stimuli) of the oddball task but the electrophysiological data recorded from the two samples in each condition also differed with regards to the patterns of activation across the scalp.

These findings are reflected in the results of the correlational analyses which indicated that greater accuracy from the dyslexics was associated with *smaller* amplitude ERPs in response to the rare stimuli. As reported in **Chapter 7**, it would again seem that those dyslexic children most able to 'fine tune' their cerebral activation from an initial "mass response" to an optimal level, particularly within this more difficult "rare stimulus" task, are the ones who achieve the greater accuracy (Kershner, 1985, 1988; Kershner & Morton, 1990). Increased accuracy of report by the dyslexics of the easier, frequent stimuli, however, was found with *greater* amplitude ERPs recorded over the left hemisphere. This relationship, between greater (frequent) accuracy and lesser left hemisphere amplitudes, was also found for the reading-age control children, it would indicate that for the detection of the simpler, frequent stimuli, the cerebral activation of both samples of children must *increase* to reach the optimal level displayed by the chronological-age controls (Harter *et al*, 1988a, b; Naylor *et al*, 1990; Hugdahl, 1995). These data would again appear to suggest that the dyslexics' problems may be, at least partly, due to some form of cognitive immaturity (as discussed in **Section 7.6.3**; see also Goldberg and Costa, 1981; Dool *et al*, 1993), and the explanations proposed for the

N100/ P200 data have again been invoked for the P300 data in the present instance (see **Section 8.6.2 (b)**).

8.7. Conclusions:

This study was undertaken to expand on the results from the previous cross-sectional studies by investigating the cognitive and psychophysiological profiles of developmental dyslexics and of carefully matched chronological-age and reading-age control children with age-appropriate reading skills. A battery of behavioural and electrophysiological measures was employed to highlight the differential processing abilities of the competent and impaired readers and to attempt to relate these to underlying differences in cortical lateralisation.

On the basis of the behavioural measures it is suggested that the cognitive processing deficits experienced by the dyslexic children are restricted to the phonological domain - as demonstrated by their substandard performance on measures of alliterative awareness, rhyme awareness and phonological memory. On these measures the performance levels of the dyslexic children were comparable with those of the younger, reading-age matched, control children. It has been hypothesised that these inferior phonological processing skills of the dyslexic children are responsible for their comparative failure to acquire age-appropriate reading skills. No differences were found between the chronological-age matched good and impaired readers on the visual measures although both samples out-performed the reading-age matched control readers. Visual capabilities, at least as indexed by performance on block design and stimulus matching tasks, are thought to more closely reflect general intellectual attainment than specific literary competence.

The data obtained from the indirect (handedness) measures of cerebral lateralisation would appear to argue against suggestions that the processing deficits of dyslexic children are the result of strictly *inter*-hemispheric cortical anomalies. The direct (electrophysiological) measures, however, indicate both *inter-* and *intra*-hemispheric anomalies in activation in the brains of the dyslexics compared with the control children. These ERP data have been interpreted as indicating that dyslexics' problems may be due to some degree of physiological immaturity, possibly coupled with the inability to suppress the inappropriate involvement of the non-dominant hemisphere during cognitive processing. This latter phenomenon may reflect a lesser degree of automaticity in the processing of linguistic stimuli in the dyslexic children than in the competent readers. Evidence linking electrophysiological and behavioural measures, in support of these suggestions, has been presented. Thus the findings of the present study would appear to support those of the previous cross-sectional studies in suggesting that the cognitive and literary impairments experienced by developmental dyslexics may be the result, not of gross structural anomalies, but of attentional and/or processing anomalies as reflected in their patterns of electrophysiological activation produced during the performance of phonological discrimination tasks. The implications of this proposal, with regards to current hypotheses concerning the aetiology of dyslexia, and to models of normal reading development, are considered in the final chapter.

~ CHAPTER 9 ~

Cognitive and psychophysiological correlates of literacy: General discussion and conclusions:

"Problem enough, this, for a life's work to learn how we read! A wonderful process by which our thoughts and thought wanderings to the finest shades of detail, the play of our inmost feelings and desires and will, the subtle image of the very innermost that we are, are reflected from us to another soul who reads us through our book"
Edmund Burke Huey (1908 p.5)

9.1 Introduction:

The present thesis sought to accomplish two fundamental aims. The first aim was to attempt to characterise and explain the relationship between children's emerging reading skills and the concomitant cognitive and psychophysiological profiles. As discussed in **Chapters 2** and **6**, much is known about the importance of specific skills in isolation, especially phonologically-mediated skills, to normal reading. Little is known, however, about the *interaction* between these skills and profiles or of the changing contributions of these cognitive skills to the initial acquisition of literacy. This situation has been determined primarily by evidence from studies that are methodologically questionable. For example, as noted in **Chapters 1** and **2**, studies have adopted cross-sectional paradigms in the investigation of what is essentially a longitudinal process (Siegel, 1994; Stahl & Murray, 1994); others have undertaken a longitudinal study but focused exclusively on a single cognitive skill to the exclusion of all others (Perfetti *et al*, 1987; Wimmer *et al*, 1991) or have employed too few testing sessions, too infrequently (Vellutino & Scanlon, 1987; Gathercole & Baddeley, 1989) and with too few subjects

(Seymour & Elder, 1986; Catts, 1991). These procedural decisions have been made largely on the basis of temporal or practical constraints, rather than theoretical or academic ones.

To date, no study reported in the reading literature has attempted to delineate the precise relationship between cognitive skills tapping different aspects of the reading process (verbal and visual) in a large sample of children across the early stages of reading acquisition. Such a paradigm was adopted in the longitudinal investigation reported in **Chapter 6**. While this exploration is important for our understanding of the processes involved in the initial development of reading, it is not sufficient to focus exclusively on the *successful* acquisition of reading. To fully understand the relationship between literacy and its underlying processes it is also necessary to demonstrate this relationship in children who *fail* to attain age-expected levels of literary competence. Consequently, **Chapters 7** and **8** served this purpose and extended the findings of the longitudinal study by measuring these same cognitive abilities in competent child-readers and in children with developmental dyslexia.

The primary objective of these cross-sectional studies represented the second aim of the present thesis: to investigate the psychophysiological concomitants of literary competence. The neuropsychology of lateralisation in normal readers and in developmental dyslexics was discussed in detail in **Chapter 4**. Psychophysiological evidence has pointed to a left hemisphere superiority for the mediation of linguistic processing in most 'normal' individuals, and to a role of the right hemisphere in the mediation of non-linguistic processing (see Galaburda, 1995 for a review). Dyslexia, however, has been suggested as the behavioural manifestation of a reduction in this pattern of inter-hemispheric lateralisation (Hynd *et al*, 1995; Boliek & Obrzut, 1995). While researchers have generally agreed that reading impairments are associated with some form of anomalous cortical lateralisation, the precise pattern of hemispheric specialisation in developmental dyslexics is unclear. As discussed in **Chapter 4**, methodological irregularities have resulted in often contradictory findings concerning the neurophysiological bases of dyslexia. The findings from **Chapters 7** and **8** indicate the extent to which neuropsychological and electrophysiological measures may be regarded as reflecting these different patterns of cortical functional lateralisation in competent and dyslexic readers. In the following sections, the findings presented in **Chapters 6, 7** and **8** are evaluated and discussed with the joint objective of determining whether the experimental questions set at the beginning of this thesis have been answered and of providing a theoretical framework in which these results might be explained and accommodated.

9.2. The cognitive context of reading I: phonological processing

It is well established that phonological processing skills are important to the initial *acquisition* of reading (Perfetti *et al*, 1987; Goswami & Bryant, 1991), to *proficient* reading (Goswami & Bryant, 1990; Rack *et al*, 1992; Hulme & Snowling, 1992) and that poor phonological skills have implications for *failed* reading (Cataldo & Ellis, 1990; Snowling, 1991). The precise direction of this relationship between phonological processing and literacy is unclear, however. As discussed in **Chapter 2**, there is much debate between one camp which advocates that phonological awareness is a necessary *pre-cursor to* reading (Goswami & Bryant, 1990; Gough *et al*, 1992) and another which argues that it is a *benefit of* reading instruction in an alphabetic orthography (Lundberg *et al*, 1988; Bertelson *et al*, 1989). The midline has been taken by those who have suggested that phonological processing skills and reading skills are 'mutually facilitating' (Perfetti *et al*, 1987; Stuart & Coltheart, 1988).

A superficial inspection of the present data may have serve to fuel this debate. The children in the longitudinal study displayed increasing phonological processing skills across the course of the investigation, from an initial state of pre-literacy to one of early reading competence, while the dyslexic children in the cross-sectional studies displayed phonological skills significantly inferior to the chronological-age control readers but equivalent to the reading-age controls. Thus, on the basis of simple analyses of variance or multiple regressions, these data may be interpreted as indicating one of two conclusions. The first is that phonological processing skills are necessary for the development of competent reading skills; the increasing phonological skills of the longitudinal sample may have contributed to the children's early reading development whereas the age-*in*appropriate reading skills of the dyslexic children may have been a product of their impaired phonological skills. A second conclusion is that the phonological processing skills of the developing readers are increasing as a result of their early grasp of, and later developing competence in, reading, while the poor reading skills of the dyslexic children may be constraining the development of their phonological skills.

The more sophisticated, partialled time-lag correlations calculated in **Chapter 6**, however, indicate that different aspects of phonological processing are crucial at different stages of reading development. As discussed in **Section 6.6.1 (c)**, awareness of rhyme in the pre-literate child significantly predicted the emergence of initial reading skills (as reported by Bryant & Bradley, 1985; MacLean *et al*, 1987). These reading skills subsequently 'fed back' into the development of rhyme awareness (see also Bryant *et al*, 1990). Thus, these data appear to reconcile the apparently contradictory viewpoints outlined above regarding the direction of the relationship between phonological processing and reading development.

The ability to perceive rhyme is reported to be present from early infancy, possibly from the age of 2 1/2 years (Chukovsky, 1963; Bruce, 1964). On the basis of this evidence, and of the findings from the longitudinal investigation reported in **Chapter 6**, it is arguable that rhyme awareness not only develops independently of reading acquisition, but that it facilitates early reading acquisition; it may do this by providing a child with the capacity to categorise rhyming words and to draw analogies between known and unknown words on the basis of shared sounds (Bradley, 1988; Goswami & Bryant, 1990). That this influence from rhyme awareness to reading ability fails to extend beyond the elementary stages of reading development may indicate that once a child has learned to focus on the sounds within the words, and to use this knowledge to facilitate reading, rhyme awareness exerts no further independent influence over reading development.

Conversely, however, the successful acquisition of elementary reading skills serves to enhance the child's subsequent ability to categorise words on the basis of the rhyme; this influence continued across the duration of the study. This may occur via an increased awareness that words may be deconstructed into individual sounds, or by directing the child to focus attention on these sub-components. This increased awareness may be via the knowledge that words which contain common letter sequences tend to share a common pronunciation (Goswami, 1986, 1988).

Reading development of the children in this longitudinal study also influenced alliterative awareness. The ability to discriminate between words on the basis of their initial sounds appears to represent a more sophisticated skill than that demonstrated in rhyme awareness (see Stanovich *et al*, 1984). In fact, in contrast to the early emergence of rhyme awareness, the ability to manipulate sub-syllabic speech sounds is thought to be absent in children prior to the onset of reading instruction (Lundberg *et al*, 1988). Goswami (1986) has reported that children are unable to draw analogies between known and unknown words on the basis of the initial sound even by the age of 5 years. The current longitudinal evidence indicated, however, that once alliterative awareness has developed it appears to enhance reading development beyond the extent of rhyme awareness. Developing reading skills in the longitudinal study also predicted future alliterative awareness in line with the findings for rhyme awareness.

As indicated above, therefore, these longitudinal data support the hypothesis of a mutually facilitative relationship between different aspects of phonological processing ability and reading development (as suggested by Perfetti *et al*, 1987; Stuart & Coltheart, 1988). This conclusion is supported by the performance of the established and failed readers in the cross-sectional studies reported in **Chapters 7** and **8**. The dyslexic children tended to demonstrate comparable phonological skills to those shown by the reading-age-matched control readers; both samples performed at a lower level than the chronological-age matched control children. In combination, these results indicate that phonological processing skills in the pre-literate child may facilitate the acquisition of preliminary reading skills. These preliminary reading skills, in turn, focus the child's attention on the sub-components within words; similarly, Bradley (1980) has suggested that seeing words in print enables children to attend to individual components within the words. This specific attentional focus then facilitates the development of the child's phonological processing skills. Thus, the relationship between phonological processing skills and reading development appears to be circular. The better the phonological processing skills of the pre-literate child, the better the initial reading development, and the better the subsequent phonological processing skills. Conversely, the poorer the phonological processing skills of the pre-literate child, the poorer the initial acquisition of literacy skills; so the impaired development progresses.

A logical consequence of this mutually facilitative relationship is that severely impaired phonological processing skills in the nursery school child impede reading development. The longitudinal and cross-sectional evidence reported in the present thesis indicates that this is the case. Therefore, while the literary competence of normal readers is a function of their age-appropriate phonological skills, the reading skills of the dyslexics, are *constrained* by their poor phonological skills. These poor reading skills, in turn, also *constrain* the development of phonological processing skills. Such a notion might provide an explanation of the observed increases in reading skill following instruction in phonological processing (Wagner & Rashotte, 1987; Byrne & Fielding-Barnsley, 1993) and of the converse increase in phonological processing skills as a result of reading instruction (Read *et al*, 1986; Morais & Alegria, 1992).

A comprehensive study of the design employed in the present longitudinal investigation, spanning 2 years of early reading development, is of tremendous importance in the domain of reading research. Unfortunately, however, the present investigation was constrained by the time available. By the age of 6 years children's reading skills are still in a fairly early stage of development. Dyslexia is generally not identified until reading ability has fallen at least 2 years behind expectations on the basis of the child's chronological-age (Pavlidis, 1990). While these children are already exhibiting considerable variations in reading ability, it is impossible to determine at this stage which, if any, of these children may suffer from specific reading impairments. An extension of this investigation, especially over the 4-5 years during which the children's reading skills are really established, would be desirable. Such an investigation would provide a unique data-base charting the developmental course of the acquisition and development of literacy skills in children. These data would enable an evaluation of the hypothesis that impaired rhyme awareness in the pre-literate child impedes the initial realisation of the relationship between shared sounds, shared letter sequences and shared pronunciations and will thus establish the child on the developmental path whereby the 'poor become poorer' (Stanovich, 1986).

9.3. The cognitive context of reading II: phonological memory

The aforementioned relationship between phonological processing skills and reading ability was reflected, to some extent, in the findings from the measures of phonological memory in the longitudinal and cross-sectional studies. The children in the longitudinal study demonstrated greater phonological memory capacity at each stage of testing. Also, at each stage, phonological memory capacity significantly predicted reading ability at the next testing stage. This influence of phonological memory over subsequent reading ability was significantly greater than the converse influence of increasing reading skills over phonological memory capacity at the next adjacent stage of testing. Evidence would appear to suggest that phonological memory capacity (as assessed by a simple measure of digit span) and reading ability may be related via the individual's general phonological skills. These are manifested in the ability to encode information phonologically and to use phonological representations to retain information in short-term storage (see Hulme & Roodenrys, 1995). Any influence of reading development on memory is posited as being a by-product of enhanced phonological processing skills resulting from early reading development (as discussed in the previous section). On this basis it is suggested that phonological memory is crucial to the acquisition of competent reading skills (see **Chapter 6**, also Gathercole *et al,* 1991).

This suggestion is endorsed by the findings of the P300 cross-sectional study, reported in **Chapter 8.** The competent (chronological-age matched) readers in this study demonstrated significantly greater phonological memory capacity than the dyslexic and reading-age matched children; these reading-age matched samples also demonstrated less developed reading skills than the chronological-age matched control children. These data, therefore, support previous suggestions that phonological memory capacity may distinguish between novice and competent readers (Johnston *et al*, 1987; Thomson, 1988) and also between competent and impaired readers (Snowling & Hulme, 1989; Hulme & Snowling, 1992). This is hardly surprising in view of the intimate involvement of memory functioning in the reading process. Memory skills are required not only in the initial acquisition of literacy skills but also to support fluent reading, such that the average skilled reader is able to accurately identify (i.e. recall from memory) any one of in excess of 30,000 words within a fraction of a second (Mitchell, 1982).

What is surprising is that this distinction was not found between the competent and impaired readers in the N100/ P200 cross-sectional study, reported in **Chapter 7**, although a trend emerged in this direction. As suggested earlier **(Section 7.6.4)**, it is possible that not *all* dyslexic children display reduced phonological memory capacity (Torgesen & Houck, 1980), just as not *all* dyslexics have impaired phonological processing skills (see Stein, 1991). It may be that extant differences in phonological memory capacity between the competent and impaired readers are not tapped by this relatively simple digit span measure although, as mentioned above, the two samples did *tend* to differ in the expected direction. As discussed previously, phonological memory differences between individual dyslexic and control readers may reflect differences in phonological processing skills; this may implicate differences in speech rate between good and poor readers, although this particular issue was not addressed in the present studies.

9.4. The cognitive context of reading III: visual perceptual abilities

Performance of the children in the longitudinal study on the visual tasks (block design and matching of letter-like forms) increased over time, as demonstrated by their increased accuracy scores at each stage of testing. On the basis of these data alone it is impossible to draw any conclusions concerning the direction of the relationship, if any, between visual perceptual skills and reading ability. The partialled time-lag correlations shed light on this relationship by indicating a significant influence of the pre-literate child's visual skills on its early reading development. Visual perceptual ability failed to exert any far-reaching influence over later reading development (as reported in **Chapter 6**). In contrast to the far-reaching effects of phonological processing and phonological memory on reading development, therefore, the influence of the visual perceptual skills assessed in this study appears to be limited. This pattern of results was predicted in **Chapter 1** on the basis of contemporary models of reading development (see, for example, Marsh *et al*, 1981; Frith, 1985). These models, discussed in **Chapter 2,** implicate visual skills only in the initial stage of reading acquisition. Beyond this stage, reading is considered to depend on linguistic rather than visual processing; hence the sustained involvement of phonological processing, discussed above.

This relative dissociation between visual perceptual abilities and reading ability is further demonstrated by the finding that the chronological-age controls and the dyslexic readers in the cross-sectional studies also exhibited comparable visual abilities on these tasks (see also Grogan, 1986; Moore *et al*, 1995). These children were of the same chronological-age but demonstrated different levels of reading competence. Both the chronological-age matched control readers and the dyslexics in the P300 cross-sectional study (**Chapter 8**) exhibited greater visual processing competence than the younger reading-age matched control children. On the basis of these data it is suggested that visual skills, at least of the sort tapped by these particular tasks, reflect not literary competence but general intellectual maturation (see Manis *et al*, 1993). Thus, it may be that the visual perceptual tasks employed in the present study assess processes which "are remote from the perceptual conditions facing a child learning to read" (Hulme, 1988, p. 373).

There is evidence that dyslexics *may* suffer impaired visual processing at the magnocellular level of the visual system (Lehmkuhle *et al*, 1993; Dautrich, 1993; Cornelissen *et al*, 1994). Yet, the ability of good and poor readers to perceive visual information, at least at the relatively high level indexed by the present tasks, is indistinguishable. The problem of highlighting visual perceptual differences between competent and impaired readers may be a result of a difficulty with identifying precisely which aspects of visual processing are relevant to reading, and with identifying tests which adequately index these aspects (Stein, 1991). The findings from the studies reported in the present thesis, in combination with evidence from the literature, would suggest that any visual perceptual differences which exist between normal and impaired readers may not emerge in the performance of static pattern processing tasks. Instead they may require the perception of rapidly changing visual information for their elicitation (see Lovegrove *et al*, 1986; Cornelissen *et al*, 1992). Future research investigating the role of visual perceptual abilities in the acquisition and development of reading skills should, perhaps, focus on these lower level perceptual skills. It should monitor, for example, the development of binocular control and the rapid processing of visual information (as discussed in **Chapters 2** and **3**). These skills are intimately involved in reading; thus the theoretical validity of such research is established.

9.5. Psychophysiological and behavioural measure of reading I: handedness

As noted in **Chapter 4**, the relationship between handedness and reading ability is generally ambiguous. Little is known about the relationship between handedness and normally developing reading skills although, as noted by Porac and Coren (1981), "shifts away from consistent and congruent dextrality can be associated with reading impairment".

To the extent that measures of handedness reflect underlying cortical lateralisation it was predicted in **Chapter 1** that changes in lateralisation which accompany reading development would be reflected in the measures of hand preference and hand skill. Indeed, as reported in **Chapter 6**, both measures from the longitudinal investigation showed signs of change over the course of the study. The hand skill measures taken at each stage of testing revealed increasing skill in both the left and the right hands over time, although overall the children demonstrated a right hand advantage; this was expected in a sample comprised of predominantly dextral children. Developmental increases in hand skill have previously been reported in children from the age of 2 1/2 years, for example, by Fennel *et al* (1983) and by Curt *et al* (1992). These changes have been interpreted as reflecting cortical maturation (see **Section 6.6.1 (b)**, also Kilshaw & Annett, 1983). This proposal is supported by the changes observed between the second and third stages of testing, spanning the period when formal literacy instruction began. Between these two stages of testing the children displayed a shift towards greater dextrality. Furthermore, the handedness variable at stage 2 significantly predicted emergent literacy skills at stage 3; this relationship was not significant at any other time.

Taken together these results appear to indicate that hand skill may provide a valid index of the cortical lateralisation underlying reading, at least during the early stages of a child's development charted in the current longitudinal investigation. Furthermore, assuming contra-lateral control of the hands, the shift towards increasing dextrality coincident with the onset of focused reading instruction would appear to reflect an augmentation in the cortical maturation of the left hemisphere at this time (see Kilshaw &

Annett, 1983). This would accord with suggestions that measures of handedness reflect the degree of hemispheric dominance for the processing of language (Annett & Kilshaw, 1983; Strauss *et al*, 1987; Annett, 1991). Supportive evidence for this is provided by the results reported in **Chapter 7**, where there was an observed relationship between greater dextrality and increased phonological processing ability. As phonological processing is mediated by the left hemisphere (see Hiscock & Kinsbourne, 1995), these data concur in providing empirical validity to the suggestion of a relationship between cortical lateralisation and handedness as assessed by a simple measure of hand skill. The theoretical validity of this relationship was discussed in **Chapter 4**.

Of some surprise, on the basis of this conclusion from the longitudinal data, is the finding of no significant differences between the competent and impaired readers in the cross-sectional studies in terms of the hand skill indices. This might suggest that it is only in the early stages of a child's cortical development that *inter*-hemispheric variables are of primary importance; as mentioned above, these possibly reflect an increase in the left hemisphere's dominance for the mediation of linguistic processing. Following this preliminary *inter*-hemispheric shift, it is proposed that further changes associated with physiological maturation are *intra*-hemispheric, as reflected by the electrophysiological data reported in **Chapter 7**. This proposition is considered in **Section 9.7** below.

Although no significant differences emerged in the hand skill *indices* between the competent and dyslexic readers in the cross-sectional studies, significant between-group differences were observed in *mean* completion times of the pegboard task. The dyslexic children performed this task with greater left *and* right hand skill than the younger reading-age controls, thus again supporting suggestions of maturational increases in skill. In the first cross-sectional study, however, the dyslexics demonstrated equivalent skill to the chronological-age controls (with both hands), whereas in the final cross-sectional study the chronological-age control readers performed significantly faster than the dyslexics, again with both hands; this finding is also reported elsewhere (Moore *et al*, 1995). This latter effect might be explained in terms of some generalised impairment in the brains of the dyslexic children which reduces their motoric skill. In view of the evidence indicating a greater involvement of the left than the right hemisphere in the execution of skilled motor movements (see also Kolb & Milner, 1981; Beaton, 1985), this "generalised impairment" may possibly reflect a dysfunction of the left hemisphere in the dyslexics (as discussed in **Chapter 4**).

If this is the case, why did this effect not emerge from the first cross-sectional study? A comparison of the data from the two studies shows that whereas the results of the dyslexic samples in each are comparable, it is the faster completion times of the control children in the second study which account for the observed difference. Both samples of children in this latter study were older than those in the former. Thus, it is possible that whereas the hand skill level of the normal readers is again showing the maturational effects discussed previously, that of the dyslexic children is relatively stagnant over time. Of course, this is speculative, and would need to be explored further through the longitudinal monitoring of the hand skill profiles of dyslexic children, or of children who become dyslexic.

Complementing the rightward bias reported from the hand *skill* measure, the hand *preferences* in the longitudinal study displayed a shift towards increased dextrality between the second and third testing stages. As discussed in **Chapter 6**, however, it is impossible to determine, on the basis of these data, the reason for this shift. Whether, for example, it is a reflection of the hypothesised increase in left hemisphere dominance discussed above, or whether it reflects increased practice in using the right hand to write, in the early stages of school life. Evidence concerning the development of hand preferences, and of the relationship between hand preference and language development is generally lacking. The present longitudinal data, however, would appear to support the use of hand preference measures as indirect indices of the cortical lateralisation umderlying the initial acquisition of reading skills.

Accordingly, hand preference measures also distinguished between the competent (chronological-age and reading-age controls) and dyslexic readers in the first two cross-sectional studies. The dyslexic children in each instance proved less right hand preferent than the normal readers. To the extent that measures of hand preference are reflective of *degree* of underlying lateralisation (Annett, 1991), these data would again support the hypothesis of a reduced left hemisphere dominance for language in the dyslexic children.

While there is some degree of inconsistency in the handedness data from the four studies, the evidence generally appears to support the use of hand skill and hand preference measures as indirect indices of degree of underlying cortical lateralisation. Once again, however, it is suggested that hand skill and hand preference measures should be considered as tapping different aspects of a common underlying dimension; perfect correlations between the results of the two measures would not, therefore, be expected. In view of the fact that different laterality indices appear to be specific to particular tasks and modalities (Salmaso & Longoni, 1985; Annett, 1992a; Eling, 1983), perhaps a fruitful objective for future studies would be to combine different measures of handedness in an exploration of the neurophysiological bases of reading development as revealed by complementary measures, rather than attempting to produce more diverse measures in the hope of finding the definitive measure of lateralisation (see Annett, 1992a; Provins & Magliaro, 1993; Bryden *et al*, 1994).

9.6. Psychophysiological and behavioural measure of reading II: dichotic listening

As discussed in **Sections 7.6.2.** and **7.11.2.**, the C-V dichotic listening paradigm failed to differentiate significantly between the good and poor readers, either in terms of total accuracy of recall or of perceptual ear advantages. Unfortunately the results from the two studies employing this paradigm were inconsistent. No particular ear advantage was obtained for the chronological-age matched competent and impaired readers in either of the recall conditions (free recall or forced recall), although both groups *tended* towards a right ear advantage in the forced recall condition. While the absence of a verbal REA receives some support from the literature (Obrzut *et al*, 1985; Duvelleroy-Hommet *et al*, 1995), it is still somewhat unexpected in the light of the conceptual underpinnings of the task (see Mehler & Christophe, 1995; Galaburda, 1995; Hugdahl, 1995). As detailed in **Section 4.4.2**, the verbal REA is the product of the expected left hemisphere dominance for the mediation of linguistic processing in conjunction with physiological asymmetries of the auditory pathways (Ahonniska *et al*, 1992; Duvelleroy-Hommet *et al*, 1995).

In line with expectations, the reading-age matched established and failed readers *did* display a right ear advantage for the perception of the C-Vs in the forced recall conditions (Hugdahl & Andersson, 1986). This is thought to reflect an enhancement of the expected perceptual bias towards the right side of space (Hiscock & Kinsbourne, 1980; Boliek *et al*, 1988). Neither group showed a verbal REA under free recall (reflecting the results from the chronological-age matched samples). This is surprising in view of evidence that previous studies employing forced attention recall conditions have found these to enhance extant free recall REAs (Hugdahl & Andersson, 1986). It is possible, however, that this lack of ear advantage under free recall may reflect an elimination of perceptual bias by the instruction to attend equally to both ears during the simultaneous, dichotic, presentations (see **Section 7.11.2.**).

The data were consistent in failing to highlight different patterns of performance by the children with established reading skills and the children with age-inappropriate reading skills. To this extent the findings would appear to argue against suggestions of anomalous inter-hemispheric functional lateralisation in the dyslexic readers, at least for the perception of dichotically presented C-V stimuli. As indicated in **Section 7.6.2.**, differential ear effects for reporting C-V syllables by good and poor readers are found less frequently than those reporting other types of dichotic stimuli (e.g. numbers or words: Mercure & Warren, 1978; Obrzut, 1989). This may be a result of the fact that the C-V stimuli are meaningless and not obviously "linguistic". Thus, they may be failing to tap any linguistic processing deficits of the dyslexic readers, leading to an absence of any between-group effects. One means of investigating this possibility would be to employ more overtly linguistic, meaningful stimuli in other studies. It is acknowledged, however, that behavioural measures alone reveal little about the actual processing which underlies the behavioural response and nothing about degree of intra-hemispheric lateralisation. In order to do this, there is a need to employ behavioural (i.e. dichotic listening) measures in conjunction with psychophysiological measures, as discussed below.

9.7. Psychophysiological and behavioural measure of reading III:ERPs

In contrast to the inconsistencies of the behavioural measures, the electrophysiological measures unequivocally indicated a degree of anomalous cerebral activation in the dyslexic children during the perception and cognitive processing of verbal information, as reflected by changes in the N100/P200 and P300 respectively.

The ERPs recorded from the control readers in each of the cross-sectional studies showed a predominantly left hemisphere bias. This finding is common in the literature (Tenke *et al*, 1993; Ahonniska *et al*, 1993; Brunswick & Rippon, 1994) and is consistent with expectations of the left hemisphere mediation of linguistic processing (Porac & Coren, 1981; Obrzut, 1989; see also **Section 4.1**). Of particular interest to the present thesis was the finding that the younger, reading-age matched, control readers and the older, chronological-age matched, control readers differed not only from the dyslexic children with whom they were matched, but also between each other. The pattern seen in the older control children was of increased left hemisphere activation with a tendency towards a temporo-parietal focus. The pattern displayed by the reading-age controls also showed a significant involvement of the fronto-central regions.

The temporo-parietal focus of activation of the older children during language processing is also noted by previous studies that have observed activity in the temporal and parietal regions during language tasks (Luders, Lesser, Hahn, Dinner, Morris, Wyllie & Godoy, 1991; Flowers *et al*, 1991; Ahonniska *et al*, 1993). Furthermore, it now appears as if the temporal region of the language-dominant hemisphere bears sole responsibility for the perception and processing of phonological information (Studdert-Kennedy & Shankweiler, 1970; see also Molfese, Molfese & Parsons, 1983). Physiological asymmetries favouring the left hemisphere's parietal operculum and temporal plane (Ratcliff, Dila, Taylor & Milner, 1980; Strauss, LaPointe, Wada, Gaddes & Kosaka, 1985), the planum temporale (Wernicke's area: Falzi, Perrone & Vognola, 1982) and the angular gyrus of the parietal lobe (Eidelberg & Galaburda, 1984) have also indicated that these regions *may* represent the neuroanatomical substrates for linguistic processing. The present study, therefore, provides further corroborative evidence localising the perception and processing of phonological information to the temporo-parietal regions of the left hemisphere, at least in children with established reading skills.

In addition to activation of these classical language areas, the younger normal readers also displayed activation of more anterior (fronto-central) regions. This pattern has been explained in terms of progressive lateralisation models of cortical development which suggest that maturational changes in functional lateralisation occur intra-hemispherically, in an anterior-posterior direction (Satz *et al*, 1990; Satz, 1991; Boliek & Obrzut, 1995). Obviously, the role played by the prefrontal regions in problem solving tasks, especially with regard to the 'verbal regulation' of such tasks (Galaburda, 1980; Falzi *et al*, 1982), cannot be ignored. The younger, reading-age control, children demonstrated poorer phonological processing skills (on the phonological oddity task and on the phonological oddball task) than the older control readers. It may be, therefore, that these children employed subvocal rehearsal to aid them in the performance of this subjectively difficult oddball task (see Beaumont, 1982). As no attempt was made in the present studies to determine the strategy employed by the children in the performance of this task it is impossible to assess this hypothesis.

Progressive lateralisation models have also been invoked to account for the pattern of activation found in the dyslexic children. These children generally showed no significant inter-hemispheric lateralisation, although some focal activation (comparable to that of the younger controls) was observed in the right hemisphere's fronto-central regions (as also reported by Rumsey *et al*, 1987). This is just one aspect of the dyslexics' electrophysiological 'signature' (Duffy & McAnulty, 1985) which suggests a certain degree of neurological immaturity in these children. The most striking difference between the activation of the good and poor readers was the increased right-hemisphere activation produced by the dyslexics. It is hypothesised that this may reflect a lesser degree of automaticity in these children's perceptual and processing skills than in those of the competent readers. The role of the right hemisphere in the processing of novel information for which no routinised codes exist has been discussed in **Section 7.6.3** (see also Dool *et al*, 1993). Thus, the excessive activation of the right hemisphere may reflect compensatory processing to offset the lack of efficiency and automaticity of processing of the left hemisphere (Harter *et al*, 1988a, b; Naylor *et al*, 1990).

Previous suggestions that this excessive right hemisphere activation may reflect the inappropriate allocation of attentional resources (as reflected in the P200, see **Section 7.6.3**) is regarded with some scepticism in the light of the finding that this pattern of activation again characterised the dyslexics in the final cross-sectional study. The focus of this study, the P300 component of the ERP, is reflective of a later stage of processing than that manifested in the P200 (Donchin & Coles, 1988).

The degree of neurological effort expended by the dyslexic children in the performance of the behavioural tasks is apparent in the large amplitudes and long latencies of their ERPs, and also in the correlational data. The dyslexic children who performed with greatest accuracy on the behavioural measures (the dichotic listening and the phonological oddball tasks) were those who displayed the lower amplitude waveforms, i.e., those dyslexics who needed to expend the least effort to perform the tasks. This is in contrast to the control children in whom greater task accuracy was associated with larger amplitude waveforms. This apparent contradiction is explained in terms of an optimal level of activation necessary for the accurate performance of a behavioural task (also suggested by Hugdahl, 1995; Richardson, 1995). Whereas the competent readers' performance on behavioural tasks reflects the degree of neural effort invested, the dyslexics' initial over-activation actually reduces the level of efficiency of the processing. The mechanisms of 'cell death' in the normally developing nervous system, whereby attrition of excess neurons leads to increased efficiency of processing, provide support to this suggestion (see **Chapter 4,** also Brown et al, 1994).

9.8. What do these results reveal about the development of reading skills?

Goswami and Bryant's (1990) 'Theory about Causes' suggests that the acquisition of literacy skills can be conceptualised as a developmental progression through which different cognitive skills and behaviours emerge as influential. Phonological processing skills (as indexed by measures of alliterative awareness and rhyme awareness) and visual perceptual skills are obviously both important in the nursery school child. The pre-literate child who is sensitive to sounds and visual forms is able to utilise this sensitivity to both discriminate between, and categorise, spoken and written language. Commensurate with the onset of formal reading instruction, this child is better able than the initially non-sensitive child to analyse individual letters and words.

In support of the models of reading development outlined in **Section 2.2**, such as Marsh *et al*'s (1981) 'Cognitive Developmental' model, or Frith's (1985) 'Three stage' model, the present data indicate that visual skills are important at the earliest stage of reading. The incipient school child is immediately exposed to the alphabet and is required not only to distinguish between individual letters but also to learn their forms and to reproduce them. Visual skills are obviously paramount in this process, as are memory skills, possibly mediated via the child's phonological processing ability (discussed below). Having facilitated the child's learning of the visual forms of letters, evidence suggests that visual skills (of the sort tapped by the measures employed in the present investigations) exert no further influence over reading development, just as reading exerts no influence over the further development of visual skills.

As discussed in **Section 2.2**, traditional "stage" models do not consider phonological processing to be involved in early reading development (see Marsh *et al*, 1981; Frith, 1985). The findings reported in the present thesis, however, actually served to highlight the importance of phonological skills during this period of development. From the outset, it is argued, children appear able to utilise awareness of the sounds of words in the learning of rudimentary grapheme-phoneme correspondence rules and in the appreciation that words with common letter sequences often share the same sounds (see Goswami & Bryant, 1990). Although this appreciation will be at a relatively superficial level at this early stage of development it will, nonetheless, enable the drawing of simple analogies to aid in the reading of unknown words (Goswami, 1986, 1988). Increased reading ability also serves to feed into the individual's phonological processing skills beyond this early stage of development. It is proposed that this effect occurs by enhancing familiarity with sub-syllabic segments of speech, enabling the child to focus on increasingly sophisticated sub-components within words; as expressed by Morais *et al* (1987), "alphabetic literacy is (almost) a sufficient indication of segmental skill" (p. 435). In this way, increased reading development will increase the accuracy and sophistication of the analogies available to developing readers (Goswami & Bryant, 1990). Thus, these data support suggestions of a mutually facilitative relationship between phonological processing and literacy skills (Perfetti *et al*, 1987; Stuart & Coltheart, 1988).

This enhancement of linguistic processing skills which occurs with the onset of formal schooling is arguably mirrored by an increase in cortical maturation of the left hemisphere, as reflected by the shift towards increasing dextrality observed in the handedness measures. The establishment of descriptive codes responsible for automatic processing within the left hemisphere (Dool *et al*, 1993) has also been discussed within the domain of increasing linguistic competence. This increase in automaticity may be conceptualised as a strengthening of the neural connections within the left hemisphere and of pruning of superfluous neurons in the right hemisphere; this may be necessary for the development and support of high level cognitive processing skills (Ellis *et al*, 1991; Brown *et al*, 1994). As observed by Naylor *et al* (1990), "Perhaps reading experience is not only a necessary condition for the full development of the neurological substrate of reading, but also essential to the development of other high level cognitive skills... Experience may serve to provide the cellular competition required for normal cell death which results in the adaptive 'pruning' required for normal brain function" (p. 152).

In relating this framework to the impairments experienced by developmental dyslexics, it is hypothesised that these children suffer some form of dominant (left) hemisphere dysfunction from early in life which impedes their development of phonological processing skills; visual skills, mediated by the non-dominant (right) hemisphere, would be spared. It is not possible to speculate on the aetiology of this hemisphere specific impairment on the basis of the current evidence, although hypotheses which have been proposed to account for such impairments have been discussed in **Section 4.3.** In view of the above discussion of the intimate relationship that develops between phonological processing skills and literacy skills, it is suggested that this reduced phonological processing competence serves to stifle the acquisition of fundamental literacy skills, beyond those acquired via visual perceptual processes. Thus, phonological processing and reading skills may be viewed as "mutually constraining" (Snowling, 1980; Bruck, 1992; Byrne *et al*, 1992). There is evidence of word recognition and phonological processing impairments in developmental dyslexics throughout life (Manis & Custodio, 1991; Bruck, 1992). It is arguable, therefore, that the impairments experienced by these individuals may be the product of fundamental *deficiencies* rather than of developmental *delays* (see **Section 3.2.1**, also Manis *et al*, 1993; Stothard & Hulme, 1995). Future studies investigating the developmental course of phonological processing skills in dyslexic children (and also in chronological-age and reading-age matched control readers) would be required to test this hypothesis.

In view of the above discussion of possible psychophysiological differences between dyslexic and competent readers, it is possible that these hypothesised cognitive deficiencies may have a physiological origin. Some factor which impairs the development of phonological processing skills in the dyslexic child may also be expressed in terms of less dextral hand *preferences*; the hand *skill* data also showed some evidence of anomalous lateralisation, as discussed above, although the dyslexic children were not overtly less dextral than the control readers. To relate these findings to the electrophysiological measures, it is possible that a left hemisphere deficit, with the resulting phonological processing impairments, would prevent the establishment of sophisticated descriptive systems for the processing of verbal information by developmental dyslexics. The resultant lack of automaticity of processing would necessitate, therefore, a greater involvement of the right hemisphere to support linguistic processing, as found in the cross-sectional studies reported in **Chapters 7** and **8**. Although the ERP waveforms showed a similar scalp distribution to those recorded from the reading-age matched control readers, suggesting *delays* in the cortical development of the dyslexics, subtle differences observed in the N100, P200 and P300 components of the waveforms further serve to support suggestions of *deficiencies* in these children, as outlined above.

The evidence would appear to support the basic tenets of Annett's (1985) Right Shift theory in that a boost to left hemisphere speech development, which occurs in the majority of brains, may fail to occur in the brains of children who develop dyslexia. Phonological processing skills (including those involved in phonological memory) would be impaired, while visual skills would develop as normal. The conceptual independence of handedness and language lateralisation, according to the right shift theory, would explain the equivocal hand skill performances of the competent and impaired readers in the cross-sectional studies. The hand preference measures, to the extent that they reflect degree of cortical lateralisation, would further support suggestions that the dyslexics are lacking a boost to the left hemisphere development of language.

9.9 Conclusion

The studies reported in the present thesis were undertaken with two fundamental aims. The first of these was to investigate the cognitive and psychophysiological concomitants of normal reading development in children from an initial state of pre-literacy to a state, two years later, of early reading competence.

In **Chapter 1** it was predicted that any extant relationship between visual perceptual abilities and reading development would be fairly transitory, and would only emerge in the very early stage of reading acquisition. This was found to be the case. It was further predicted that measures of phonological processing ability and phonological memory would exhibit a more far-reaching relationship with reading development, although the precise nature of this relationship was unknown. Accordingly, both phonological processing skills and phonological memory correlated with reading across the duration of the present longitudinal investigation, and also predicted reading ability over subsequent stages of testing. Whereas phonological memory predicted reading ability at each subsequent stage of testing throughout the study, the predictive power of reading ability over subsequent phonological memory was limited. In contrast, while phonological processing competence in the pre-reader significantly predicted reading ability over the early stages of the investigation, the mastery of early reading skills was sufficient to significantly feed into and predict subsequent phonological processing skills.

As discussed in **Chapter 4**, evidence has linked impaired reading ability and phonological weakness with an absence of the expected left hemisphere dominance for the mediation of linguistic processing. Phonological processing and reading ability have also been linked with handedness such that impaired readers, characterised by poor phonological processing skills, are most likely to be situated towards the left of the hand skill continuum. Thus, it was predicted that the acquisition of preliminary reading skills would be associated with measures of handedness; specifically, that any increase in left hemisphere dominance that accompanied early reading development would manifest as increased right handedness over this period. As reported in **Chapter 6**, the handedness of the children in the longitudinal study (assessed through a combination of hand skill and hand preference measures) *did* exhibit a pattern of increased dextrality coincident with the onset of formal literacy instruction. This finding was interpreted as reflecting an increase in left hemisphere dominance for the processing of linguistic information, prompted by the onset of focused instruction in the processing of written language, i.e. reading instruction.

In line with current stage models of reading development these findings have been interpreted as indicating that children approach reading by treating it initially as a purely visual task. Even a fairly rudimentary level of reading skill is sufficient for most children, however, to equip them with the linguistic skills necessary to support the development of competent reading. Thus, normal reading development follows a course in which a mutually supportive relationship between phonological processing skills and the acquisition of literacy skills is significant. The emergence of this relationship is dependent upon the establishment of an optimal degree of hemispheric dominance for the processing of linguistic information. This process appears to take the form of an increase in cortical maturation of the left hemisphere commensurate with the onset of formal reading instruction, and is reflected, to some extent, in simple measures of handedness.

A second aim of the studies reported in the present thesis was to investigate the cognitive and psychophysiological concomitants of established and failed reading. It was predicted that the cognitive skills necessary to support the normal development of proficient reading skills would distinguish between competent readers and developmental dyslexics. Specifically, it was predicted in **Chapter 1** that the dyslexics would be impaired relative to the competent readers of the same chronological-age on measures of phonological processing and phonological memory. The level of involvement of visual perceptual skills in reading development is relatively unknown, although visual perception was also posited as a variable which may distinguish between the chronological-age matched competent and impaired readers. Comparisons were also made between dyslexic children and reading-age matched control readers on these same measures. Similarities in the cognitive abilities of these latter matched samples were expected to indicate delays in the cognitive development of the dyslexics, which may underlie their reading impairments.

The evidence reported in **Chapters 7** and **8** generally corroborated and extended the findings of the longitudinal study. The fundamental importance of phonological processing and phonological memory skills to reading was again apparent; the children with the superior reading skills (the chronological-age matched control readers) also demonstrated the superior competence on these cognitive measures. The children matched on the basis of reading-age, however, exhibited comparable phonological processing and phonological memory skills. The converse pattern emerged from the visual perceptual data. Whereas the chronological-age matched competent and impaired readers were indistinguishable on the basis of their perceptual skills, both out-performed the younger competent readers. It was once again suggested, therefore, that whereas the influence of visual perceptual skills (of the sort indexed by the measures employed in the present studies) is minimal, phonological processing and phonological memory skills are intimately involved in the development of age-appropriate reading skills. Poor phonological skills in the pre-reader may serve to subsequently constrain the acquisition of reading skills, thus initiating the process characterised by the "Matthew effect" (Stanovich, 1986).

It is hypothesised that some physiological anomaly may be responsible for the phonological processing difficulties of dyslexic children. Such an anomaly may result from the absence of a boost towards left hemisphere dominance for the processing of language. The direct and indirect indices of cerebral lateralisation were somewhat equivocal on this matter, however. The handedness measures taken in the cross-sectional studies failed to highlight differences in the *direction* of cortical lateralisation between the competent and impaired readers, although these measures have been interpreted as providing some evidence of a lesser *degree* of lateralisation in the dyslexic children than in the controls. The results of the dichotic listening task were disappointing in that they failed to differentiate between the dyslexic and the control children. These results may have been confounded, however, by the particular stimuli employed. Consonant-vowel syllables are not overtly linguistic; thus, as discussed in **Chapter 7**, it is possible that these stimuli failed to tap the particular processing impairments experienced by the dyslexic readers. While the dichotic listening data failed to shed any light on the processing deficits of the dyslexic children, the results of the phonological oddball task, and the electrophysiological measures taken in each of the cross-sectional studies, were of considerable importance. These data combined to reveal a pattern of anomalous cognitive and physiological development in the dyslexic children, relative to the chronological-age and reading-age matched control readers. These findings have been interpreted as reflecting a certain degree of neurological immaturity in the dyslexic children which has impeded the establishment of routinised codes for the processing of linguistic information. The implications of this suggestion, with regards to reading development, have been discussed.

The investigations reported in the present thesis contribute a great deal to the literature concerned with the development of normal and abnormal aspects of reading development. They have addressed all three levels of the framework proposed by Frith (1995) to explain the integration of the factors involved in reading; they have provided detailed evidence of the emergence of different cognitive skills intrinsically involved in the initial acquisition and subsequent development of normal reading skills; they have provided evidence of the inter-relationships between these measures; they have revealed the specificity of the cognitive processing deficits experienced by developmental dyslexics;

they have highlighted electrophysiological anomalies in the brains of dyslexic children, relative to both chronological-age and reading-age matched control readers; they have revealed the utility of simple measures of handedness as indirect indices of the degree of underlying cortical lateralisation; and they have demonstrated the relationship between cognitive, behavioural and electrophysiological measures taken contemporaneously. Yet, in spite of the comprehensiveness of the research reported here, and of the vast literature on which it is based, much remains unknown about the cognitive and psychophysiological mechanisms underlying reading.

The importance of the findings reported in the present thesis is apparent. Future investigations are called for to develop the hypotheses proposed on the basis of these findings. An extension of the longitudinal investigation reported in **Chapter 6** would provide a unique data-base delineating the changing relationships between the cognitive and psychophysiological factors intimately involved in the development of children's reading skills. In such a large sample of children it may be confidently expected that some will emerge as developmentally dyslexic. The theoretical importance of profiling the entire developmental course of dyslexia, for our understanding of the mechanisms which underlie normal and abnormal reading development, is undeniable. The practical importance of such a profile, with regards to the future identification of dyslexia in children, is also beyond question.

Regarding the future investigation of the psychophysiological profiles of existing dyslexics, it is suggested that electrophysiological investigations should be pursued. By focusing on different components of the ERP it should be possible to further elucidate the extent of the linguistic impairments experienced by developmental dyslexics. The N400 component, for example, reflects auditory and visual word recognition at the semantic level (see Connolly & Phillips, 1994). An investigation of the relevance of this component to the reading difficulties experienced by dyslexic children would present as an obvious development of the cross-sectional studies reported in the present thesis.

In conclusion, the remark made by Huey in 1908 and cited at the start of this chapter, is again appropriate. While the enormity of the task involved in researching the "wonderful process" of normal and abnormal reading development is acknowledged, it is hoped that the work presented in the present thesis will serve to convince "another soul who reads ... through our book" that the investigation of the cognitive and psychophysiological correlates of literacy is a fruitful area worthy of further research. As noted by Richardson (1989), "In spite of a century of study, the mechanisms of speech and language disorders, especially in children, remain challenging problems". We are now well-equipped to meet these challenges.

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~Appendix 1~

Digit span test

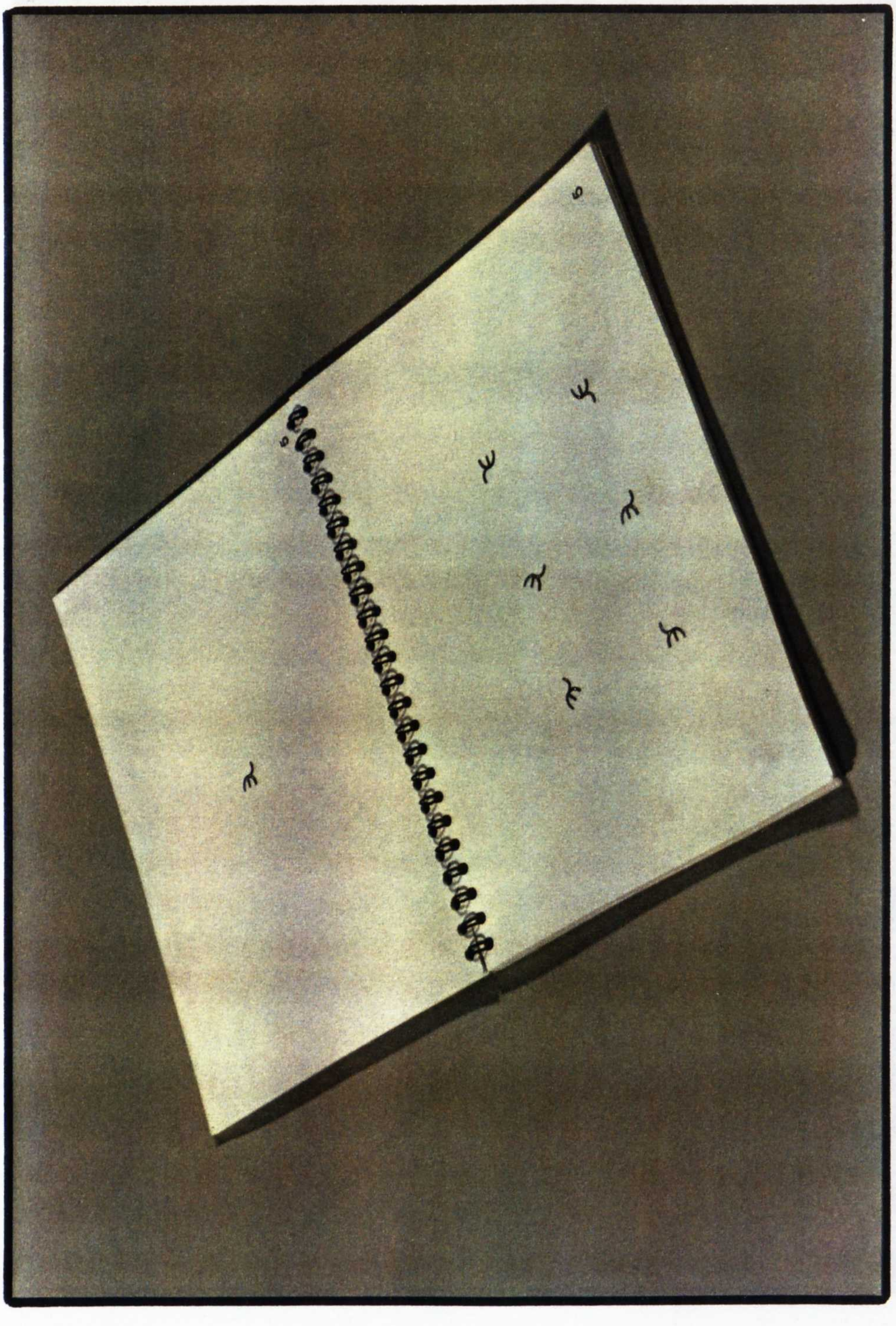
(British Ability Scales, Elliott *et al*, 1983)

Item	Number
1	44
2	23
3	54
4	92
5	75
6	866
7	242
8	564
9	756
10	483
11	5877
12	3238
13	8956
14	8495
15	6159
16	57667
17	57736
18	56964
19	23746
20	95247
21	922828
22	545457
23	162997
24	417432
25	751946
26	8845517
27	2438224
28	2914139
29	2569874
30	5814726
31	23233626
32	58878446
33	38896152
34	25837461
35	447575616
36	928414375

~Appendix 2~

Matching of letter-like forms task

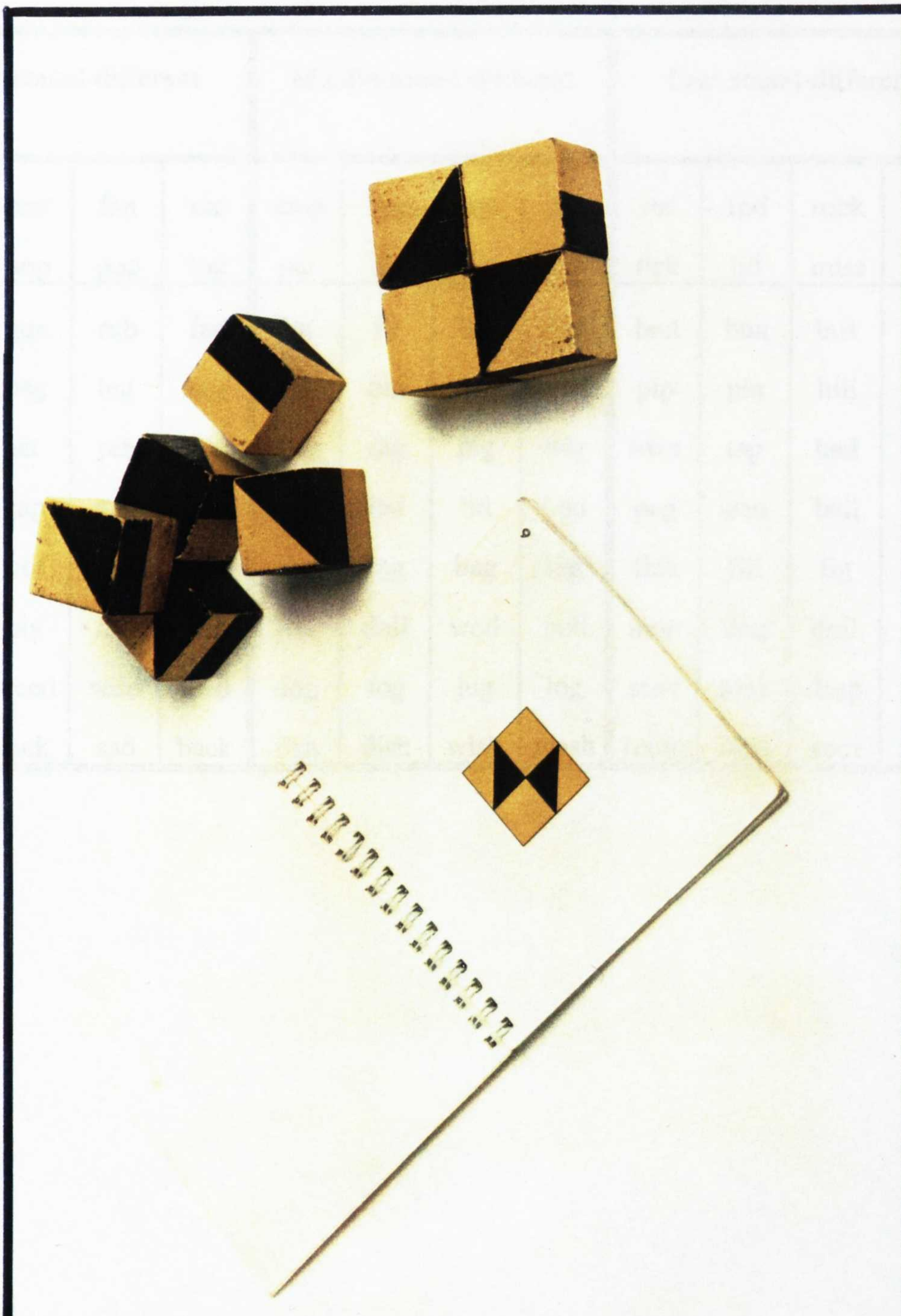
(British Ability Scales, Elliott *et al*, 1983)



~Appendix 3~

Block design task

(British Ability Scales, Elliott *et al*, 1983)



~Appendix 4~

Phonological oddity task

(Bradley & Bryant, 1983)

First-sound-different				Middle-sound-different				Last-sound-different			
hat doll	mat hop	fan pop	cat top	mop pat	hop fit	tap bat	lop cat	rot lick	rod lid	rock miss	box lip
sun	gun	rub	fun	pat	fit	bat	cat	bud	bun	bus	rug
hen	peg	leg	beg	fun	pin	bun	gun	pip	pin	hill	pig
fin	sit	pin	win	hug	dig	pig	wig	ham	tap	had	hat
map	cap	gap	jam	red	fed	lid	bed	peg	pen	bell	pet
cot	hot	fox	pot	wag	rag	bag	leg	fish	fill	fig	kick
fill	pig	hill	mill	fell	doll	well	bell	mop	dog	doll	dot
peel	weed	seed	feed	dog	fog	jug	log	seed	seal	deep	seat
pack	lack	sad	back	fish	dish	wish	mash	room	food	roof	root

~Appendix 5~

Word reading test

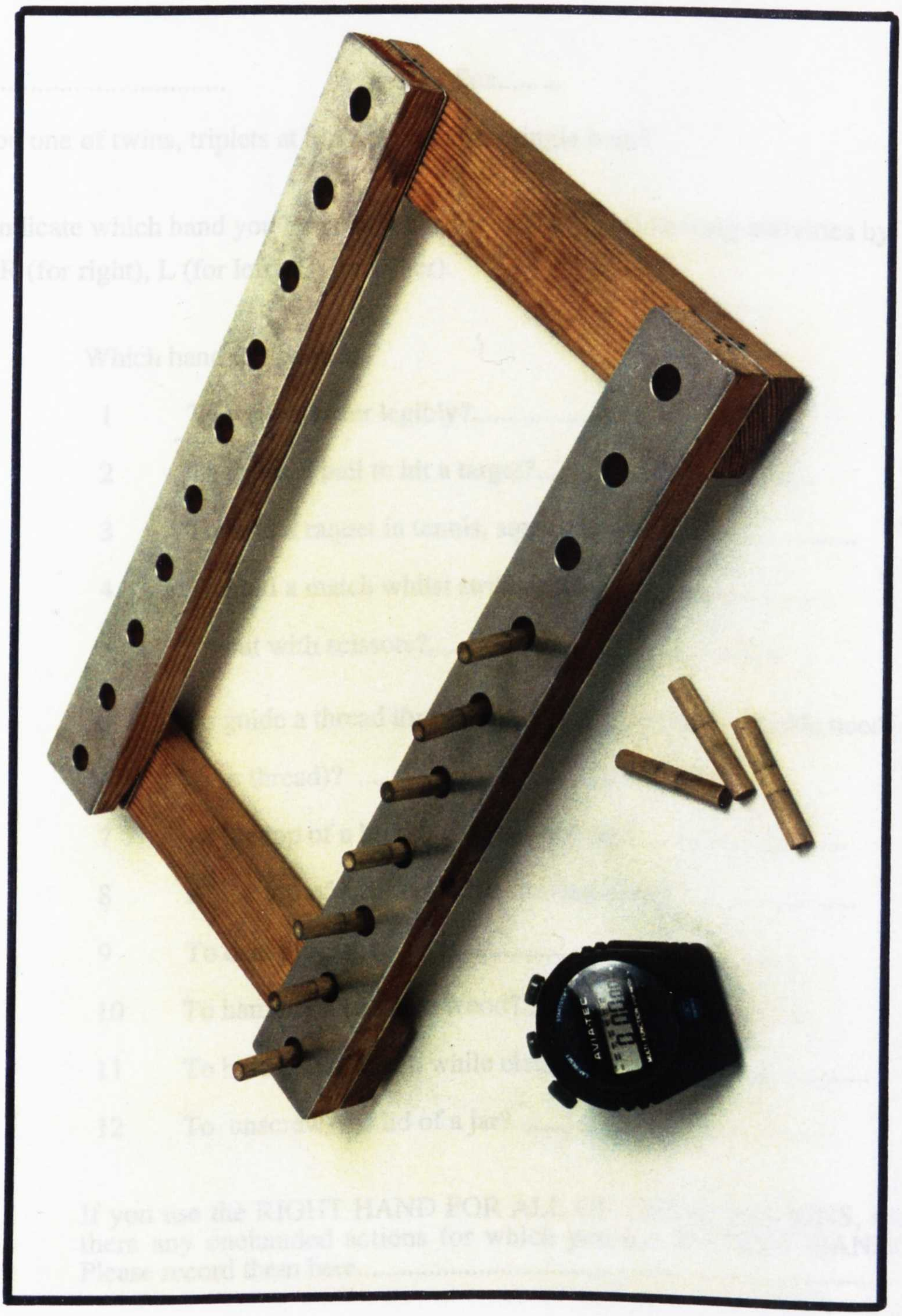
(British Ability Scales, Elliott *et al*, 1983)

sport
collect
army
invite
drab
travel
leather
massive
tentacle
lethal
error
exert
divulge
beard
curiosity
transparent
nomadic
universal
velocity

~Appendix 6~

Pegboard task

(Annett, 1970, 1985)



~Appendix 7~

The Annett Hand Preference Questionnaire

(Annett, 1970, 1985)

Name................................. Age...... Sex.........

Were you one of twins, triplets at birth or were you single bom?

Please indicate which hand you habitually use for each of the following activities by writing R (for right), L (for left), E (for either).

Which hand to you use:

1 To write a letter legibly?..

2 To throw a ball to hit a target?...................................

3 To hold a raquet in tennis, squash or badminton................

4 To hold a match whilst striking it?................................

5 To cut with scissors?..

6 To guide a thread through the eye of a needle (or guide needle on to thread)? ....

7 At the top of a broom while sweeping?............................

8 At the top of a shovel when moving sand?........................

9 To deal playing cards?...

10 To hammer a nail into wood?......................................

11 To hold a toothbrush while cleaning your teeth?.................

12 To unscrew the lid of a jar?..

If you use the RIGHT HAND FOR ALL OF THESE ACTIONS, are there any onehanded actions for which you use the LEFT HAND? Please record them here..

If you us the LEFT HAND FOR ALL OF THESE ACTIONS, are there any one-handed actions for which you use the RIGHT HAND? Please record them here..

~Appendix 8~

Dichotic listening stimuli

(Hugdahl & Anderssen, 1987)

BA DA GA TA PA KA

~Appendix 9~

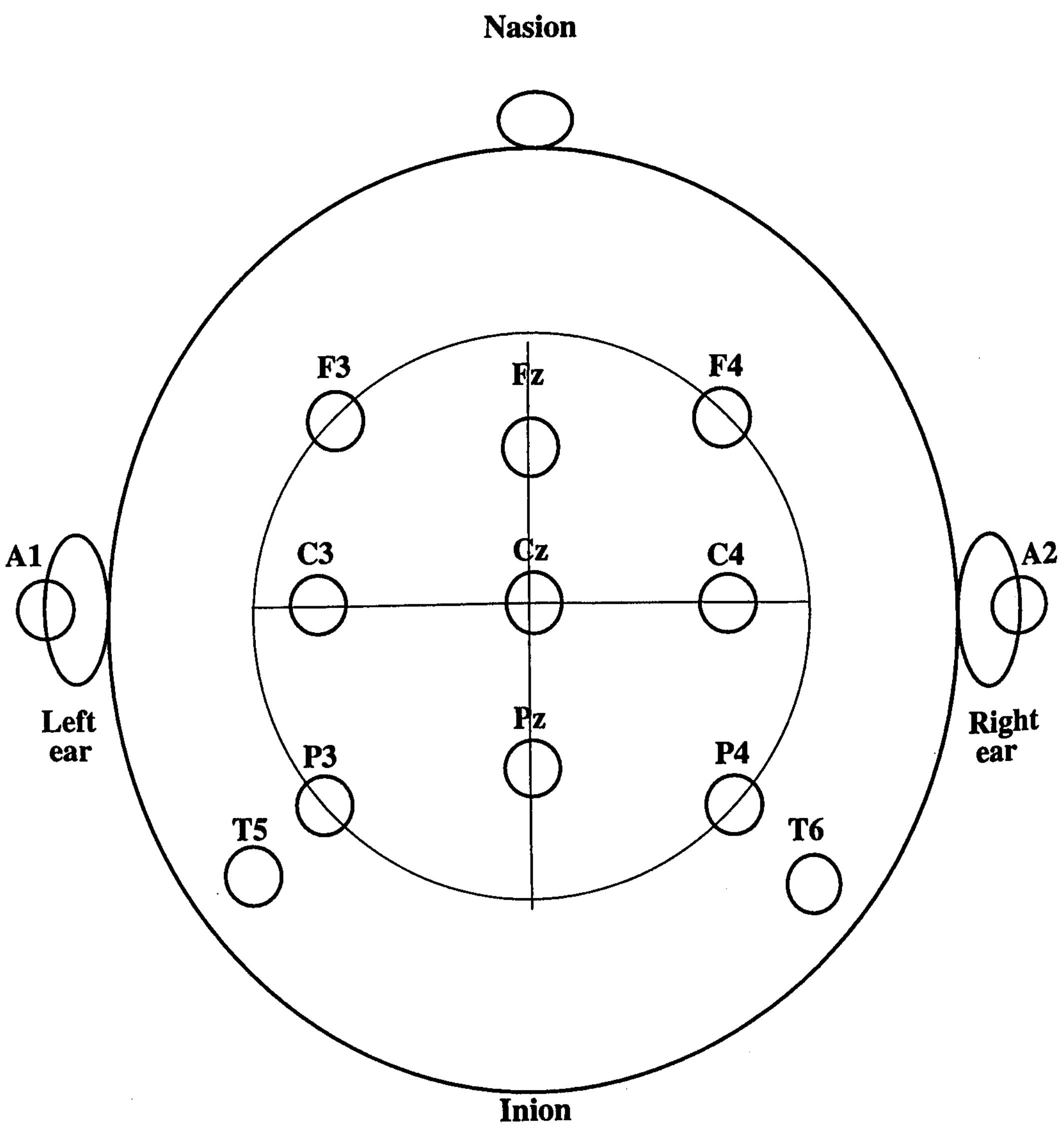
Phonological oddball task stimuli

First-sound-different			Middle-sound-different			Last-sound-different		
Library:	Stimulus:	Duration (msecs):	Library:	Stimulus:	Duration (msecs):	Library:	Stimulus:	Duration (msecs):
Frequent:	Bat	445.11	*Frequent:*	Red	424.75	*Frequent:*	Cat	448.02
	Back	400.02		Fed	509.11		Hat	482.93
	Ban	552.02		Bed	356.38		Mat	731.65
	Bad	379.65		Dead	434.93		Bat	449.47
	Bag	400.02		Led	475.65		Sat	619.65
	Ban	552.02		Head	477.11		Fat	541.11
	Bam	433.07		Said	535.29		Pat	498.93
	Bap	482.93		Wed	453.84		Rat	501.84
Rare:	Tap	490.20	*Rare:*	Fad	589.84	*Rare:*	Fan	488.75
	Mat	488.75		Bud	386.93		Sad	776.02
	Fan	497.47		Lid	474.93		Rag	461.11
	Sack	517.84		Had	530.93		Pan	462.56
	Rag	445.11		Mud	446.56		Mad	449.47
	Ham	475.65		Cod	418.93		Cap	475.65
	Mad	404.38		Sad	776.02		Ham	509.11
	Cat	465.47		Did	368.02		Bag	388.38

~Appendix 10~

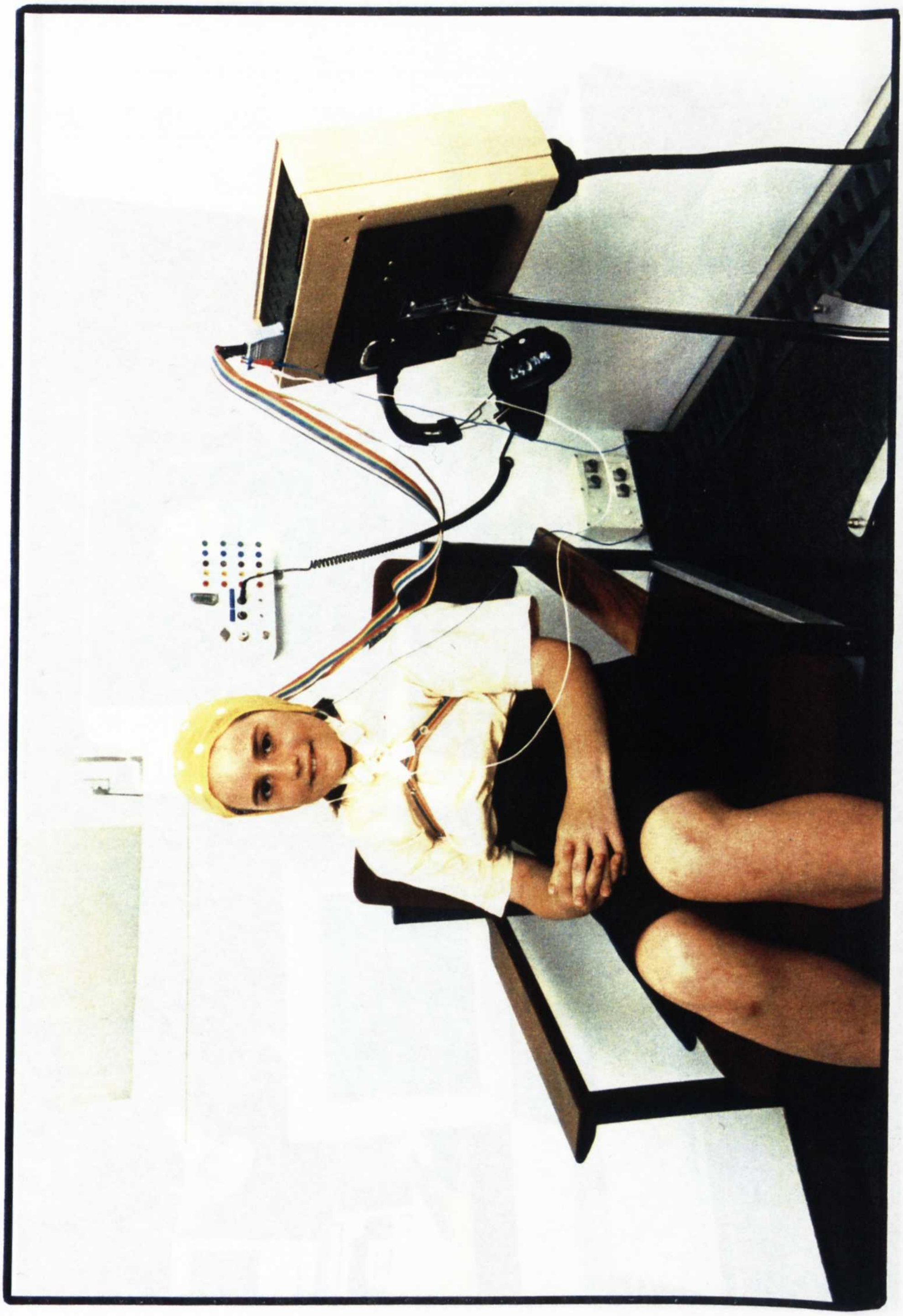
The 10/ 20 electrode placement system

(Jasper, 1958)



~Appendix 11~

The experimental set-up:



~Appendix 12~

The NeuroScience (Series III) Brain Imager:

~Appendix 13~

Correlation coefficients between the variables over the course of the longitudinal investigation:

Table 1. Correlation coefficients between the measures at stage 1.

	PegL	PegR	BBF	BBM	BBL	Digits	Blocks	Letters	Reading
PegL	1.00								
PegR	0.70**	1.00							
BBF	0.08	-0.04	1.00						
BBM	-0.13	-0.12	0.53**	1.00					
BBL	-0.18	-0.16	0.43**	0.58**	1.00				
Digits	-0.11	-0.17	0.12	0.14	0.18	1.00			
Blocks	-0.17	-0.20	0.04	0.18	0.14	0.22	1.00		
Letters	-0.25	-0.26	-0.02	0.08	0.14	0.29*	0.46**	1.00	
Read	.	.	.	.	.	.	.	.	1.00

Table 2. Correlation coefficients for the variables at stage 2.

	PegL	PegR	BBF	BBM	BBL	Digits	Blocks	Letters	Reading
PegL	1.00								
PegR	0.61**	1.00							
BBF	0.08	-0.06	1.00						
BBM	-0.00	-0.05	0.15	1.00					
BBL	0.05	-0.08	0.10	0.14	1.00				
Digits	-0.15	-0.29*	0.16	0.11	0.17	1.00			
Blocks	-0.16	-0.24	0.13	-0.02	0.22	0.36**	1.00		
Letters	-0.36**	-0.31*	-0.03	0.14	0.07	0.17	0.42**	1.00	
Read	-0.10	0.05	-0.10	-0.13	-0.01	0.16	0.19	0.07	1.00

** $p < 0.005$ * $p \leq 0.05$

Table 3. Stage 3 correlation coefficients

	PegL	PegR	BBF	BBM	BBL	Digits	Blocks	Letters	Reading
PegL	1.00								
PegR	0.58**	1.00							
BBF	-0.10	-0.08	1.00						
BBM	-0.04	-0.16	0.13	1.00					
BBL	-0.02	-0.04	0.18	0.29	1.00				
Digits	-0.10	-0.20	0.18	0.05	0.29	1.00			
Blocks	-0.18	-0.25	0.14	0.27	0.11	0.36**	1.00		
Letters	-0.33*	-0.29	0.16	0.29	0.10	0.31*	0.60**	1.00	
Read	-0.23	-0.23	0.10	0.28	0.19	0.25	0.45**	0.31*	1.00

** $p < 0.005$ * $p \leq 0.05$

Table 4. Stage 4 correlation coefficients for each pair of variables.

	PegL	PegR	BBF	BBM	BBL	Digits	Blocks	Letters	Reading
PegL	1.00								
PegR	0.46**	1.00							
BBF	-0.15	-0.21	1.00						
BBM	-0.14	-0.02	0.41**	1.00					
BBL	-0.07	-0.01	0.32*	0.57**	1.00				
Digits	-0.22	-0.10	0.21	0.37**	0.37**	1.00			
Blocks	-0.19	-0.21	0.40**	0.45**	0.31*	0.46	1.00		
Letters	-0.21	-0.19	0.17	0.25	0.23	0.34	0.49	1.00	
Read	-0.19	-0.25	0.29	0.42**	0.23	0.39	0.39	0.32	1.00

** $p < 0.005$ * $p \leq 0.05$

Table 5. Correlation coefficients at the final stage of testing.

	PegL	PegR	BBF	BBM	BBL	Digits	Blocks	Letters	Reading
PegL	1.00								
PegR	0.70**	1.00							
BBF	0.08	-0.04	1.00						
BBM	-0.13	-0.12	0.53**	1.00					
BBL	-0.18	-0.16	0.43**	0.58**	1.00				
Digits	-0.11	-0.17	0.12	0.14	0.18	1.00			
Blocks	-0.17	-0.20	0.04	0.18	0.14	0.22	1.00		
Letters	-0.25	-0.26	-0.02	0.08	0.14	0.29*	0.46**	1.00	
Read	.	.	.	.	.	.	.	.	1.00

** $p < 0.005$ * $p = 0.01$