Phonological Representations in Dyslexia: Nature, Influences and Development

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Abstract

Developmental dyslexia is a specific difficulty in acquiring literacy skills that manifests despite normal IQ, adequate educational opportunity and in the absence of any obvious sensory or neurological damage. According to the Phonological Representations Hypothesis a core deficit for individuals with dyslexia across languages is a brain-based difficulty in accurately storing the sound sequences that make up words, or 'phonological' representations.

In this thesis the Phonological Representation Hypothesis (PRH) of dyslexia was tested and elaborated. Twenty-four dyslexic children alongside chronological age and reading age matched groups were assessed over a three-year period.

Consistent with the PRH, associations were found between the quality of the dyslexic children's phonological representations, as indexed by picture naming, and their performance on related input and output phonological processing tasks based on the same lexical items.

Possible reasons for the underspecificity of dyslexic phonological representations were also investigated at cognitive and perceptual levels. The sensitivity of dyslexic individuals to the presence of similar-sounding words within their mental lexicon, 'phonological neighbourhood density', was assessed. Across a range of phonological awareness tasks the dyslexic group were found to be as sensitive to this lexical factor as their age peers.

Perception of amplitude envelope onsets (AEOs) was also investigated. AEOs are an auditory parameter associated with speech rhythm and were hypothesised here to be important for the establishment of well-specified phonological representations. Dyslexic insensitivity to AEO variation was seen longitudinally through both behavioural and neurophysiological assessment. These findings suggest that for some dyslexic children perception of basic rhythmic speech cues may play a role in their phonological representation deficit.

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Chapter 1 – Phonological representations, their nature and development

1.1 Introduction

Developmental dyslexia is in a lot of ways, an unexpected learning difficulty. Typically the first sign of it in children is problems in literacy learning which seem out of step with the rest of the child's academic progress. Such children are often bright and otherwise performing well, however the translation of sounds to written symbols for reading and spelling is inordinately difficult. It is now clear that dyslexic children have difficulty reflecting upon the sounds within words, or 'phonological' processing. The definition given by the Orton Dyslexia Society of the USA (1994) was that "dyslexia is one of several distinct learning disabilities. It is a specific language-based disorder of constitutional origin characterised by difficulties in single word decoding, usually reflecting insufficient phonological processing abilities. These difficulties in single-word decoding are often unexpected in relation to age or other cognitive abilities; they are not the result of generalised developmental disability or sensory impairment. Dyslexia is manifested by a variable difficulty with different forms of language, including, in addition to a problem with reading, a conspicuous problem with acquiring proficiency in writing and spelling."

Much research has tried to explain the so-called 'phonological deficit' in dyslexia. Due to the pervasiveness of its effects a prominent idea has arisen that dyslexic children are failing to mentally *represent* the sound patterns of words in their language in a detailed and specific manner. This is the Phonological Representations Hypothesis of dyslexia, a hypothesis both tested and elaborated in this thesis.

Before describing these investigations, however, it is important to consider what we know about phonological representations in typical development. In this chapter, we firstly examine what is known about the nature of fully-developed phonological representations. This is followed by an introduction to 'phonological awareness', directly dependent upon the integrity of phonological representations and investigated extensively in this thesis. The development of both phonological representations and phonological awareness are then discussed. Currently no one model can adequately account for the empirical developmental data amassed in these areas and so the chapter ends with synthesis of the current evidence and a working framework of phonological representation development, within which the thesis findings can be examined.

1.2 The nature of phonological representations

When acquiring language, an early process is the linking of semantic referents to specific combinations of sound. The stored forms of these sound sequences are the 'phonological representations' of words and over the course of language acquisition many thousands of phonological representations must be stored in a way to allow accurate recognition across different speakers and acoustic contexts, accurate production and later, the development of orthographic connections.

The exact nature of fully developed phonological representations is not yet understood. It is generally assumed that their internal structure corresponds to the hierarchy of units developed in phonological theory. Language is a system and as such contains a finite number of elements that can be combined contrastively. In phonology these elements tend to be provided by the peaks and troughs of energy or stricture within the speech stream. Across languages, syllables are units of relative prominence and within each syllable the point of maximal acoustical energy is provided by the obligatory vowel. Typically a syllable can then be divided into an *onset* consonant and a *rime*, the latter containing the vowel and an optional coda (for example, c-ot). Onsets, nuclei and coda can all be either simple or complex depending upon whether they contain single or multiple *phonemes*. Phonemes are the smallest sound units used contrastively to signal meaning differences within a language. Research has shown, however, that none of these elements have invariable physical traits but rather their identity is also characterised by their relation to other elements. The determination of phonological units requires reference to both the properties of the speech signal as well as to the phonological 'system' as a whole.

This lack of absolute physical correlates points to a further attribute of phonological representations, which is their abstractness. Whilst *phonetic* segments can be identified at a 'surface' level of perception, recognition of phonological units such as phonemes involves additional cognitive processes such as categorisation and normalisation across contexts. Although oft-cited, the difficulty for Japanese learners of English, in distinguishing between the phonemes /r/ and /l/, which do not form a phonological contrast in Japanese, demonstrates well the distinction between surface phonetic differences and language-specific phonological contrasts.

The abstract nature of phonological representations makes their direct investigation difficult. Thus, although it is accepted within cognitive psychology that phonological processes are distinct to semantic processing, three alternative architectures of phonological representation have been posited: (1) a single phonological network; (2) coupled input and output phonological networks; and (3) independent input and output phonological networks. It is beyond the scope of this thesis to determine which of these models holds most promise. However, given that it is common to have both input and output phonological processes affected by brain damage in adults (Martin & Saffran, 2002), and in the light of recent evidence from fMRI (functional magnetic resonance imaging) studies (Scott & Wise, 2004), it is likely that input and output phonological processing are functionally and anatomically highly connected. An assumption of highly coupled input and output phonological networks will thus underlie the investigations of this thesis.

1.3 Phonological Awareness

From how phonological representations have been described so far, it is clear that the information they encode about the sound patterns in words is abstract. In such a form it will not be available for conscious reflection. Although we do not consciously reflect upon phonological information in spoken word production and recognition, reflection upon phonological information is necessary in order to become literate. Reading and writing require facility in converting the individual sounds within words, phonemes, into arbitrary written symbols, or graphemes. In effect reading and writing are cultural tools that give spoken language a greater physical permanence. They are not acquired automatically but must be explicitly taught.

The ability to carry out this conscious reflection upon the sounds in words is called, 'phonological awareness'. Phonological awareness is generally conceptualised in terms of the hierarchy of units underlying phonological representations i.e. syllables, onset-rimes and phonemes. This conceptualisation has shaped how we measure phonological awareness, which also focuses upon these three levels. An activity to assess an individual's awareness of the syllables in words might entail 'tapping out' or counting the syllables in a given word, judging which word of a pair has the greater number of syllables or matching words according to their syllable number. For onset-rime awareness, one might be asked to judge if two words share the same rime[1], to generate words with the same rime or to identify the word within a spoken list that does not share the same rime as the others. Finally, at the phoneme level, often referred to specifically in the literature as 'phonemic awareness', typical activities might include judging whether two words share the same initial or final phoneme, segmenting a word into all its constituent phonemes or deleting a phoneme from a word and saying aloud the resultant word form.

The difficulty of phonological awareness tasks generally increases as the size of the phonological unit being targeted decreases. However, it is also very important to note that whatever the unit being targeted, the sheer breadth of ways used to assess phonological awareness also adds many other cognitive demands to the activity. Taking phoneme deletion as an example, if a child was asked to delete /l/ from 'plot' and say the resulting word, in order to successfully complete this task the child must first:

[1] The linguistic term 'rime' is used here, which refers to the vowel +/- coda within a single syllable.

- perceive the given word and the phoneme to delete
- retain both these items in memory for the duration of the task (an existing phonological representation of the word 'plot' might also help here, as well as semantic information etc.)
- avoid interference from words and phonemes of previous trials
- segment the given word , in order to separate the 'l' from its neighbouring sounds, then delete the /l/
- re-synthesise the remaining sounds to form a word
- compare this newly formed word to existing phonological representations/lexical knowledge in order to find a likely match
- verbally produce the word 'pot'

In having to explicitly demonstrate phonological awareness, the child is engaging a host of other cognitive processes from perception and short-term memory through to long-term stored knowledge and executive function. This is largely unavoidable (though see chapter 8 for neurophysiological techniques that can partially circumvent these problems), however, it is an important consideration when employing phonological awareness tasks to address specific questions about phonological and cognitive processing.

Another point that the hierarchy of phonological awareness activities raises is the question of development – what do we know about the developmental progression of both phonological representations and phonological awareness? It is to this issue we now turn.

1.4 The development of phonological representations and phonological awareness

It has so far been established that phonological representations are a way of storing the sound sequences that make up words in an abstracted form, that allow recognition and production of words across multiple speaking and listening conditions. Phonologists have posited that these representations have a hierarchical internal structure and conscious knowledge of this internal structure is known as phonological awareness.

As will be expanded upon in the next chapter, this thesis takes the position that in developmental dyslexia an individual's phonological representations are somehow 'underspecified'. This implies that in the course of development, dyslexic children have experienced difficulties in establishing representations adequate for the recognition and production of words across all conditions. It is assumed that these difficulties are subtle, as they become obvious only when the dyslexic child has to use their phonological representations for unusual tasks such as reflecting on the internal sound structure of words or in acquiring literacy.

In order to be able to examine this hypothesis in more depth we need an understanding of how phonological representations are established in normal development and how this leads on to a more explicit awareness of the sound structure of words indexed via phonological awareness.

1.4.1 The establishment of phonological representations

Understanding the process of phonological representation establishment has been a notoriously difficult area of enquiry for two main reasons. Firstly, due to their inherent abstractness, phonological representations can not be investigated directly. As we will see in this and subsequent chapters, researchers have developed convincing indices of representational quality, however the issue of indirectness remains. Secondly, because unlike literacy, spoken word recognition and production are a universal human necessity, phonological representations are being established from the earliest stages of infancy – this again makes investigation more difficult. It does not make it impossible however, and by exploring infant behaviour using tools such as preferential-looking patterns and responses to novelty, a great deal has now been learnt.

We know, for example, that infants can discriminate the phonological contrasts of their own language by the age of two months (Kuhl, 1987) and are sensitive to language-specific vowel prototypicality by six months (Kuhl, Williams, Lacerda, Stevens & Lindblom, 1992). Such studies are ground-breaking in that they have made people aware of perceptual abilities in infancy previously assumed not possible. They have also shown that processing limitations attributed to infancy may sometimes be an artefact of investigative unreliability/insensitivity.

However, knowing that infants can perceive and distinguish phonological detail at the finest level is not evidence that they are also encoding such detail to long-term phonological representations. This point is well illustrated in a study by Stager and Werker (1997). Using a release-from-habituation task, these researchers found that 14 month old infants failed to discriminate between the minimal pair 'bih' and 'dih' when presented as referents, however in an accompanying discrimination task where the syllables were not linked to referential targets the children succeeded in the task. In a subsequent word learning study (Werker, Fenell, Corcoran & Stager, 2002) of 14, 17 and 20 month olds, Werker et al. showed that by 17 months of age, but not 14 months, children could represent newly-learnt words in enough detail to distinguish slight differences. Werker et al. attributed this developmental change to the reaching of a critical vocabulary threshold, triggering finer-grain phonological encoding.

The idea that vocabulary growth drives phonological representation specificity is also central to the Lexical Restructuring Theory of Walley and colleagues (Walley, 1993; Metsala & Walley, 1998). In this theory, Walley et al. suggest that in infancy and early childhood phonological representations are initially holistic in form, with increasingly detailed representation developing primarily in response to vocabulary growth. Despite the intuitive appeal of this idea and the preliminary evidence we have of a representational 'shift' around the time of an infant's vocabulary spurt (see also, Locke, 1997), more recent research suggests this cannot be the whole story. Most notable is the work of Swingley and Aslin (2000; 2002). These authors examined the looking behaviour of toddlers between 18 and 24 months when asked to direct their gaze at one of two pictures, the name of one being either pronounced accurately (e.g. 'dog') or slightly mispronounced (e.g. 'tog'). On average the toddlers looked at a target picture more when its name was pronounced correctly than when it was mispronounced. The size of this effect, however, was *not* related to age or vocabulary size. This finding was also replicated with 14 month old infants in a subsequent study (Swingley and Aslin, 2002), as well as by other researchers (Bailey and Plunkett, 2002). In the search for clues as to what drives phonological specification forward, Bailey and Plunkett (2002), as well as looking at factors such as age and vocabulary size, also looked 'within' vocabulary at lexical factors such as word familiarity and the number of similar sounding neighbours a word has (phonological neighbourhood density). Using the same preferential looking paradigm with 12-48 month olds and a 30 word pool, no performance effects from these variables were, however, observed.

Thus, we have strong evidence for the sophistication of infants' phonological perception skills, with emerging evidence that this has direct relevance to the representation of first words. However, as Bailey and Plunkett (2002, p.1281) also point out, "above chance responding in an inter-modal preferential looking task or in a habituation switch task is indicative of some detail in young children's phonological representations but not necessarily of full phonological specification". The role of vocabulary growth in driving phonological specification at this stage is not yet understood. Although there is some suggestion of its influence, synthesis of the current evidence favours a more interactive explanation. For whilst vocabulary size remains small yet phonological perception skills are well-developed, perhaps the phonological information an infant is extracting from the continuous speech stream in an effort to 'crack the code' is most influential at this stage. Recent work by Jenny Saffran and colleagues (Saffran, Aslin & Newport, 1996; Saffran, 2003) showing infants' ability to abstract and *retain* phonological information concerning speech categories and word boundaries through statistical learning of occurrence probabilities certainly points to the feasibility of such a process. Saffran et al. (1996) exposed 8 month-old infants to a spoken nonsense language in which the only cues to word boundaries were the sequential probabilities of syllable sequences. Following a brief exposure infants were successfully able to discriminate 'words' of the nonsense language from syllable sequences spanning word boundaries. Phonological sequence probabilities will themselves be made accessible through the accent and marking provided by syllabic rhythm and stress, further pointing towards the importance of accurate perceptual analysis as a precursor to representation establishment.

Once phonological representations become established and the child`s own internal vocabulary grows, further refinement of phonological representations and their mobilisation for the demands of literacy may increasingly depend upon the nature of this *internal* lexicon. Such an idea is examined further in the next section, where the development of phonological awareness is explored.

1.4.2 The Development of Phonological Awareness

Through its more explicit nature and later developmental emergence, there is a larger degree of consensus in studies of phonological awareness development. Using the types of measures described in section 1.3., evidence has now accrued from many languages that children's phonological awareness follows a developmental progression from syllable and onset-rime awareness to later phonemic awareness. In typically-developing children, syllable and onset-rime awareness are observable before school-age. Syllable awareness has often been assessed using a tapping task. Liberman, Shankweiler, Fischer and Carter (1974), for example, found in a sample of American 4-6 year olds that 46% of the 4 year olds, 48% of the 5 year olds and 90% of the 6 year olds demonstrated an ability to tap out the number of syllables in a series of one to three syllable words, the 4 and 5 year old children in this study being pre-readers. Cossu, Shankweiler, Liberman, Katz & Tola (1988) reported a similar developmental trend in Italian children with syllable awareness shown by 67% of 4 year olds, 80% of 5 year olds and 100% of a 7-8 year old (school-age) sample.

The oddity task is another phonological awareness measure that has been usefully employed across languages and can be used to assess onset-rime awareness. In the oddity task children hear a list of spoken words and have to decide which is the 'odd one out' on the basis of either the onsets, vowels or codas. Difference judgements for initial sounds can thus be made on the basis of the onset, whilst difference judgements for vowels and codas can be made on the basis of the rime. With British children Bradley and Bryant (1983) demonstrated that preschool 4 and 5 year old children were above chance on both onset and rime versions of this task. Average scores were 56% and 71% correct for onset and rime judgements respectively. Similar results have been found in other languages, for example in a sample of German 6 year old preschoolers, Wimmer, Landerl and Schneider (1994) reported accuracy results of 44% and 73% for onsets and rimes respectively.

Phoneme awareness is more intimately related to the beginning of formal reading instruction (Perfetti, Beck, Bell & Hughes, 1987) and evidence suggests that as well as predicting future reading progress (e.g. Muter, Hulme, Snowling & Taylor, 1998; Hulme, Hatcher, Nation, Brown, Adams & Stuart, 2002), its emergence is actively encouraged by the process of learning to read. Mann and Wimmer (2002), for example, compared the phonemic awareness skills of American kindergartners, who are taught letters and sounds prior to schooling, with those of German kindergartners, who are not. The American kindergartners far outstripped their German peers in phonemic awareness performance. Burt, Holm and Dodd (1999) further document the rapid growth of phonemic awareness in 4 year old British children, with performance on phoneme segmentation progressing from 8% to 25% correct within this single year.

Therefore, the developmental progression of phonological awareness skill is much easier to observe than the establishment of phonological representations. However, there is still a question as to what drives this process forward. In discussing this issue with respect to phonological representations it was concluded that whilst vocabulary growth could play a role, the importance of perceptual learning in early infancy was a further critical factor. Phonological awareness develops significantly later and its emergence is probably in part precipitated by cognitive developments that enable the child to reflect upon non-immediate events. By this stage the child also has a much larger vocabulary and the role of vocabulary composition in encouraging explicit phonological awareness may thus be more influential.

Vocabulary can be examined at both a 'global' level, in terms of overall size, but also at a 'local' level. Local factors are sensitive to individual variations within this overall vocabulary expansion. Two such factors are the familiarity of individual words, as well as their phonological similarity to other words within the lexicon, the latter known as phonological neighbourhood density. A study by Metsala (1999) looked at both global and local vocabulary factors and their relationship to phonological awareness performance. Looking first at the global associations between a receptive vocabulary measure and performance on phonological awareness tasks, Metsala found that the two were closely associated in a sample of sixty one 4-5 year old children, even when phonological short-term memory ability was partialled out. In further experiments which included over one hundred 4-6 year old children, the children performed better on both an onset-rime and phoneme blending task for highly familiar words as opposed to less familiar words. Finally, in a sample of thirty-six 3-4 year olds, children's performance was superior in onset-rime and phoneme blending activities if a word had many versus few similar sounding neighbours. These observations of an intimate relationship between vocabulary and phonological awareness are also supported by other studies, both those taking a global approach (e.g. McBride, Wagner & Chang, 1997), as well as those looking specifically at factors such as word familiarity (e.g. Garlock, Walley & Metsala, 2001) and phonological neighbourhood density (e.g. De Cara & Goswami, 2003).

However, just as discussed in relation to initial phonological representation establishment, development is an interactive process and so vocabulary is unlikely to be the sole influence upon phonological awareness development. There is evidence, for example, that perceptual phonemic category boundaries are being sharpened even as children approach adolescence (Walley & Flege, 1999, Hazan & Barrett, 2000), which will affect phonological awareness skill. We also know that environmental factors such as reading instruction itself can have facilitatory effects upon phonemic awareness (Morais, Cary, Alegria & Bertelson, 1979; Mann & Wimmer, 2002).

1.5 Summary

It is apparent that the answer to the question of what drives phonological representation specificity and phonological awareness development will be multi-factorial. However, in attempting to explore the phonological deficit in developmental dyslexia we have a framework within which to work, which necessitates consideration of both perceptual and lexical influences. These factors consequently provide the basis for all the empirical work described in chapters 5-8. In the chapter that follows developmental dyslexia will be introduced in more depth and the tenets of the Phonological Representations Hypothesis discussed. This will be followed by consideration of what we know, firstly about lexical factors and dyslexia and secondly, about auditory perceptual factors and dyslexia. The experimental work carried out in order to further our understanding as to the possible impact of these factors is then reported.

Chapter 2 – Dyslexia and the Phonological Representations Hypothesis

2.1 Introduction

Developmental dyslexia is a specific learning disability that has a history by no means free from controversy; although the disability's validity is no longer questioned, its definition, breadth and underlying causes remain areas of fertile research. In the pages that follow a working definition will first be delineated which will motivate the selection criteria of the subsequent experiments. What is understood of the nature of the core phonological deficit will then be explored and some outstanding questions highlighted.

2.2 Towards a working definition of developmental dyslexia

Developmental dyslexia is a specific learning disability that is generally identified as a severe difficulty in acquiring written language despite receiving adequate instruction, having normal intelligence and lacking obvious sensory or neurological damage. It is estimated to affect approximately 5 to 17.5 % of the population (Shaywitz, 1998).

There is clearly an issue as to how severe an individual's reading difficulties should be to be classified as dyslexic. However, in considering where the severity cut-off lies, one also hits the bigger question of whether dyslexia represents a statistically distinct "hump" at the lower tail (Rutter & Yule, 1975) of the normal distribution of reading ability or whether it is simply an extreme example of normal variation in reading skill (e.g. Pennington and Lefly, 2001; Snowling, Gallagher & Frith, 2003). This question can be investigated in many ways, however perhaps the most exciting light is currently being shed by neuroimaging and genetic linkage studies.

Neuroimaging studies have identified a number of key brain regions associated with the reading process, notably the inferior frontal lobe, posterior superior and middle temporal gyri and the temporoparietal supramarginal and angular gyri (Eden & Zeffiro, 1998; Shaywitz, Pugh, Jenner, Fulbright, Fletcher, Gore & Shaywitz, 2000; Simos, Breier, Fletcher, Bergman & Papanicolau, 2000). Consistent processing differences have been observed between dyslexic and normal readers in a number of these regions, most notably the angular gyrus (Horwitz, Rumsey & Donohue, 1998; Pugh et al. 2000). Processing differences in dyslexia are also reported in electrophysiological studies (e.g. Baldeweg, Richardson, Watkins, Foale & Gruzelier, 1999; Kujala, Myllyviita, Tervaniemi, Alho, Kallio & Näätänen, 2000; Helenius, Salmelin, Richardson, Leinonen and Lyytinen, 2002), which can examine the exact time-course of neural processing. Electrophysiological recording is employed within the current thesis and so discussed in more depth in chapters 4 and 8.

Genetic linkage studies paint a similar picture to the neuroimaging literature in that distinct genetic profiles can be seen in dyslexia. Again, however, there does not appear to be a single locus of difference but rather areas upon a number of chromosomes which have now been implicated. Specifically these are on chromosomes 1, 2, 3, 6, 15 and 18 (Grigorenko, 2001; Fisher et al., 2002), with loci on chromosome 6 the most commonly replicated to date (Demonet, Taylor & Chaix, 2004).

What these converging lines of research confirm is that the "distinct hump" versus "normal variation" dichotomy is too crude a conceptualisation of dyslexia epidemiology. Certain individuals may be born with identifiable biological risk factors for dyslexia, however, the specificity of these biological vulnerabilities will vary and their interaction with the environment will always be unique. This latter point is well-exemplified by studies demonstrating the power of the environment, through effective training programmes, to alter perceived reading diagnosis (Vellutino, Snowling, Fletcher & Scanlon, 2004), and even patterns of neural activation (Simos et al., 2002).

The dyslexic children in this thesis have been selected according to the severity of their reading difficulties and the absence of other factors which could have impacted upon their presenting reading profile. These factors include general intellectual level, documented exposure to social or educational deprivation, sensory impairment or clinically significant manifestations of other developmental difficulties such as attention-deficit hyperactivity disorder (ADHD), dyspraxia or speech and language problems. It is certainly not a position taken in this thesis that dyslexia can only be diagnosed in the presence of an average or above-average IQ (cf. Vellutino, 1979). However, as with the other exclusionary criteria mentioned, in trying to understand how reading difficulties can be specifically impaired, it is logical to study children manifesting as *specific* a difficulty as possible.

2.3 Investigative levels of dyslexia

A useful aid to conceptualising the relationships between causal mechanisms and presenting behaviours in dyslexia is the model of Frith (1997). This is shown in Figure 2.1.

Figure 2.1 Frith's causal model of dyslexia

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Defining dyslexia as a specific reading difficulty is an explanation of the problem at a behavioural level. However, as a learning difficulty, it is assumed that observed reading and writing behaviours will be caused by unseen mental, or cognitive processes. Frith argues that by pinpointing anomalies at the cognitive level, one has the power to show that apparently varied behavioural symptoms can have a unified cognitive causality. The explanation of dyslexia as a difficulty in manipulating the sounds of words, the phonological deficit, is a causal explanation at the cognitive level. Logically, this cognitive anomaly may itself result from neuro-biological differences and so this makes up the final explanatory layer in the model. The model also highlights the importance of the environment as a possible influence at any of these levels.

2.4 Dyslexia and the phonological deficit

2.4.1 The nature of the phonological deficit in dyslexia

Having discussed the behavioural definition of dyslexia, we now turn to its cognitive signature. A very robust finding is that of a "phonological deficit" in dyslexic children. There is a well-established causal connection between children's phonological awareness and their ability to read and spell (Goswami & Bryant, 1990). Concomitantly, the difficulties that dyslexic children manifest on a range of phonological processing and awareness tasks have been posited as accounting at a cognitive level for their experienced literacy difficulties (Goswami & Bryant, 1990).

From chapter 1, however, it is clear that even limiting the core deficit of dyslexia to a phonological one leaves many possible levels of breakdown. As well as necessitating the basic integrity of each phonological representation, behavioural success demands the accurate deployment of these, both unconsciously in activities such as speaking and listening, as well as consciously in phonological awareness tasks and literacy. Phonological representations also have a hierarchical structure and so lack of specification at any of these levels of word, syllable, onset-rime or phoneme during the execution of a task could adversely affect performance.

Accordingly, hundreds of studies have been carried out which explore the performance of dyslexics on varied phonological processing tasks tapping one or more of these processing levels. Although the varied severity, comorbity and age of sample groups create inevitable discrepancies in the literature, pervasive deficits are reported. For descriptive ease these are frequently distilled in the literature into three main categories of phonological processing: phonological awareness tasks, verbal short-term memory and speeded naming of objects (Morris et al., 1998).

A resulting question is how the mass of positive findings and contrived imposition of task typology can inform us as to the level of phonological breakdown occurring in developmental dyslexia. Logically there may be either one single cognitive deficit or more than one, and influential theories have arisen to advocate both these possibilities. Perhaps the most notable example of a multi-factor theory is the Double Deficit Hypothesis of dyslexia espoused by Wolf, Bowers and colleagues (Bowers & Wolf, 1993; Wolf & Bowers, 1999; Wolf, Bowers & Biddle, 2000). Because of its significance this hypothesis will be reviewed below, however, as will be seen, its validity is compromised through both theoretical and methodological weaknesses. An example of a single factor hypothesis is the Phonological Representations Hypothesis. This hypothesis currently holds greater promise and so is reviewed in more depth. As will be seen, however, there are still claims of the hypothesis requiring empirical substantiation. Testing of these claims forms the first part of this thesis' empirical investigation.

2.4.2 The Double Deficit Hypothesis of dyslexia

Through the Double Deficit Hypothesis of dyslexia, Wolf, Bowers and their co-workers propose that three subtypes of dyslexia exist: one caused by a phonological deficit; a second caused by a naming speed limitation, which disrupts orthographic processing and reading fluency; and a third, more severe subtype, caused by a combination of both other deficits. It is purported that the naming speed deficits are due to a disruption to the 'precise timing mechanism' that normally influences the temporal integration of phonological and orthographic components of printed words. With this asynchrony, orthographic patterns cannot be induced automatically and so word recognition remains slow and effortful. Despite tentative support for this hypothesis, largely through studies looking at statistical clustering of performance and relationships between phonological, speeded naming and literacy skills (see e.g. Wolf et al. 2000), there are also serious theoretical and methodological challenges to be levied. In theoretical terms, the idea of a 'precise timing mechanism' lacks the specificity that would allow empirical validation. In addition, the idea that speeded naming relies on a *serial* process of orthographic recognition would not appear to fit with current models of orthographic processing (e.g. Grainger & Jacobs, 1996). Methodologically, as pointed out by Torgesen et al. (Torgesen, Wagner, Rashotte, Burgess & Hecht 1997), reported studies advocating the Double Deficit Hypothesis have typically not controlled for autocorrelation effects, created by the shared variance that rapid naming and phonological skill have with reading performance. In a longitudinal study addressing this issue Torgesen et al., found that once the influence of initial reading performance was considered prior to predictive relationships between speeded naming, phonological skills and later reading ability, only phonological skill accounted for unique variance.

2.4.3 The Phonological Representations Hypothesis of dyslexia

An alternative, single factor hypothesis is the Phonological Representations Hypothesis of Dyslexia (e.g. Snowling, Goulandris, Bowlby & Howell, 1986; Fowler, 1991; Hansen & Bowey, 1994; Elbro, 1996; Metsala, 1997b; Swan & Goswami, 1997a,b). In an attempt to account for the very pervasive nature of dyslexics' phonological difficulties a number of researchers have hypothesised that these difficulties could be fundamentally linked to the processes involved in establishing basic phonological representations. Children with dyslexia could have difficulty in establishing, storing and consequently retrieving phonological representations to the same degree of detail as their normally-reading peers. The resulting phonological representations have been variously referred to as 'fuzzy', 'indistinct' or 'underspecified' and this lack of distinctness or segmental specificity has been held responsible for the range of phonological processing difficulties observed.

Because of the abstract nature of phonological representations alluded to in chapter 1, the Phonological Representations Hypothesis has been difficult to test directly. However, through a number of studies using complementary techniques, a significant degree of empirical support now exists.

2.5 Evidence supporting the Phonological Representations Hypothesis of dyslexia

One of the earliest studies to raise the possibility of a core dyslexic difficulty in establishing phonological representations was that of Snowling, Goulandris, Bowlby & Howell (1986). As part of this study nineteen 9-12 year old dyslexic children were administered word and non-word repetition tasks, with and without noise masking. The dyslexic children were matched with both chronologically age-matched as well as reading-level matched controls. All three groups were affected equally by noise masking, making more errors in its presence. Of greater interest, however, were the group differences in repetition performance according to stimulus type. Whilst all groups could repeat back the high frequency words at an equivalent level of accuracy, the dyslexic group fell behind their age-matched peers in low frequency word repetition and behind both control groups in nonword repetition. The authors reported that the dyslexic children's deficit could not be attributed solely to input phonological processing, as noise masking should have then had a differential effect. The deficit could not be attributed to output phonological processing, as in this case a difficulty across all stimulus classes should have been observed. Also being able to rule out the possibility of a generally reduced lexicon driving the repetition deficits, the authors concluded that the most plausible explanation for these findings was a difficulty in establishing long-term phonological representations for lexical items.

This conclusion is supported by a parallel literature that has explored the picture naming abilities of dyslexic individuals. Picture naming is a skill very dependent upon the integrity of phonological representations and has consistently been found to be compromised in dyslexia. In the seminal study of Denckla and Rudel (1976) for example, dyslexic children between 8 and 11 years named significantly fewer pictures correctly than both a non-dyslexic learning disabled group as well as chronologically- and general ability-matched peers. The dyslexics' performance on a receptive vocabulary measure, the Peabody Picture Vocabulary Test (PPVT; Dunn & Dunn,

1981) was above the average level estimated for their age matched peers. Denckla and Rudel concluded that the picture naming errors of the dyslexic children could not be attributed to depressed lexicon size per se but rather, were the result of problems related to the process of linguistic retrieval. They further observed in the error patterns of the dyslexic children "correct circumlocutions, pantomimed demonstrations or associative paraphasic responses predominated" (p. 12). Such a pattern suggested that limited access to phonological rather than semantic information was affecting performance for these children.

Later studies have both confirmed and built upon these basic findings. Katz (1986), for example, looked more closely at the effect of word properties on picture naming performance. He found that both poor readers (selected as reading below local norms) and their age-matched controls made more errors on low frequency pictures than high frequency pictures. Katz also found that the poor readers manifested a particular drop in performance on objects with *long*, low frequency names, which the average and good readers did not show. This difficulty, confirmed by subsequent studies to not be attributable to articulatory limitation (Katz, 1996), was taken as further evidence of the phonological nature of the naming difficulties, with longer words making higher demands upon phonological memory than shorter words. Other studies have also both confirmed the basic finding of dyslexic naming difficulties with a probable phonological locus (e.g. Wolf & Goodglass, 1986; Murphy, Pollatsek and Well, 1988; Snowling, von Wagtendonk and Stafford, 1988; Rubin, Bernstein and Katz, 1989; Rubin, Zimmerman and Katz, 1989; Wolf & Obregon, 1992; Nation, Marshall & Snowling, 2001; Swan & Goswami, 1997a; Faust, Dimitrovsky & Shacht, 2003), as well as validating the use of picture naming as an index of phonological representation quality.

A further elaboration of the Phonological Representations Hypothesis comes from the work of Carsten Elbro. In a series of studies (Elbro, Neilson & Petersen, 1994; Elbro, 1996, 1998; Elbro, Borstrom & Petersen, 1998) Elbro has advocated that the phonological difficulty observed in children and adults with dyslexia can best be typified with the concept of representational 'distinctness'. Distinctness, according to Elbro's definition refers specifically to "the magnitude of the difference between a representation and its neighbours" (Elbro, 1998, p149) and this is a determinant of the completeness and accuracy of the representation as well as the ease of access to sublexical phonological units of the representation. Elbro has proposed that those who are at-risk of, or who are overtly manifesting a dyslexic profile have reduced access to the most distinct variants of spoken words. In order to index 'distinctness' Elbro adopted a novel approach, examining individual's perception and production of vowels in syllables where the vowel is vulnerable to reduction, e.g. the unstressed vowels in 'crocodile'. Looking at the links between spoken word production and reading performance Elbro found, for example, in a sample of 49 children of dyslexic parents, that this measure of the distinctness of phonological representations based on vowel articulation was a particularly sensitive predictor of reading two years later (Elbro et al. 1998). Reduced access to fully distinct representations has also been reported in adults (Elbro et al., 1994).

As a whole, the studies mentioned in this section would appear to give preliminary credence to a conceptualisation of dyslexia through the Phonological Representations Hypothesis. Snowling et al.'s study (1986) points towards representation-driven input and output phonological processing difficulties. Numerous studies of picture naming deficits in dyslexia support the idea that phonological representations remain fragile within this group. Elbro et al.'s studies further emphasise that whilst dyslexic individuals can lay down a rudimentary phonological representation, assessment of the degree of fine-grained specificity consistently demonstrates a subtle 'indistinctness'.

Despite their immense value, these studies do not provide watertight evidence for the adequacy of the Phonological Representations Hypothesis. Ideally, more direct evidence is needed. One way of obtaining this would be to examine whether less well-specified phonological representations for *particular* lexical items cause phonological processing difficulties in tasks *based on those items*. There are just three specific tests of this nature in the literature. Two of these, Constable, Stackhouse & Wells (1997) and Swan and Goswami (1997b), involved children, whilst the third, by Dietrich and Brady (2001), published once this thesis was already underway was a study of adult poor readers. Because of the importance of their methodology and rationales to the experiments described in chapter 5, each will be outlined more fully below.

2.5.1 Constable, Stackhouse and Wells, 1997

Constable et al. reported a single case study of a 7 year old boy called Michael with severe word-finding difficulties and reading delay (Constable et al., 1997). The main aim of the investigations reported was to ascertain the possible levels of breakdown in lexical access for Michael. Initial assessment using a range of standardised measures suggested more phonological processing difficulties than semantic difficulties. Phase two of the investigation then investigated Michael's phonological difficulties in more depth. Tests of picture naming, auditory lexical decision, auditory-visual lexical decision and word/nonsense word repetition were all constructed using the same lexical items. Where nonwords were used, these were derived from the actual words by a systematic manipulation of the segmental structure, through the perseveration or transposition of phonemes. Michael's performance on all these tasks was at least 2 standard deviations below that of control children. An item-by-item analysis revealed that the same lexical items were responsible for the naming and phonological difficulties. Constable et al. thus argued that Michael's naming difficulties arose directly from his imprecise phonological representations of particular words, rather than from motor, semantic or other deficits.

2.5.2 Swan and Goswami, 1997

The second specific test of the relationship between poor phonological representational quality and other tasks involving phonological processing comes from a study of 11 year old dyslexics by Swan and Goswami (1997b). Swan and Goswami directly compared picture naming accuracy with phonological processing performance, however their study focused upon phonological *awareness* ability at three phonological levels – syllable, onset-rime and phoneme. Before each experimental trial children were shown the pictures for which phonological judgements would be expected and were asked to name these. This assessed the children's unprompted access to the correct phonological representation. The phonological awareness tasks were then presented in a standard way, with the experimenter repeating the correct name and requesting the appropriate phonological awareness judgement. At the syllable level children were asked to tap out the number of syllables in a set of 24 mono- and polysyllabic words. Onset-rime and initial phoneme/final phoneme tasks were carried out in which the experimenter read aloud pairs of monosyllabic words and children had to decide whether the pairs had sounds in common. For the phoneme tapping task children heard either CVC, CVCC or CCVC words and were asked to tap out the number of sounds that they could hear in the name. Results were then examined in terms of unadjusted performance levels as well as performance adjusted to include only those experimental trials for which picture naming had been accurate. Once representational specificity was controlled for in this way dyslexic phonological awareness performance was comparable to both age- and reading-level matched controls at the sublexical units of syllables, onsets and rimes, though a lag was present in comparison to both these groups on the phoneme-level tasks. Swan and Goswami concluded from these findings that in dyslexia the availability of a phonological representation's sublexical units for analysis depended upon the accuracy and retrieval of the phonological representation as well as the linguistic level tapped. One limitation of this study, however, was that differing procedural demands confounded with the variation of linguistic level, reducing the strength of conclusions about the availability of respective sublexical units.

2.5.3 Dietrich & Brady, 2001

In the study of Dietrich and Brady 25 adult poor readers, alongside adult skilled readers and adolescent reading-level matched controls were assessed using paired confrontation naming and spelling tests. The authors found that the adult poor readers were able to name fewer pictures than the adult skilled readers, though were at approximately the same level as the adolescent group (with receptive vocabulary levels controlled). The poor reader group was significantly worse than both groups in spelling accuracy and interestingly, naming inaccuracy influenced their spelling significantly more often than it did the other groups. A further novel aspect to this study was the repetition of the naming test on two occasions, to assess naming stability. Dietrich and Brady hypothesised that a phonological deficit may contribute to less stable performance and indeed this was borne out in the results. Less skilled readers produced a phonological error at Time 1 and a different phonological error at Time 2 four times as often as the adult skilled reader group and twice as often as the adolescent reading-level controls. Even when the less skilled readers realised a word correctly at Time 1 they were less likely to do so on the second occasion compared with the other groups. The authors concluded that indistinct phonological representations would be more likely to yield such variable patterns of production.

2.6 Summary and Research Goals

This chapter has provided a working definition of dyslexia as well as discussing an influential cognitive level hypothesis of causality, the Phonological Representations Hypothesis. The Phonological Representations Hypothesis has wide-ranging empirical support and a growing number of studies show evidence of item-specific relationships between phonological representations as indexed by picture naming performance and accuracy in both input and output phonological processing tasks. However, although the three studies outlined in sections 2.4.1-3 have been very useful in providing the methodologies and ideas to explore this area, there are certain outstanding questions:-

With regard to the Constable et al. (1997) study:-

If item-matched input and output processing tasks, such as those used by Constable et al., were administered to a *group* of dyslexics *without* significant speech and language difficulties, would the finding of word-specific relationships be replicated?

With regard to the Swan and Goswami (1997b) study:-

If word-specific relationships between naming performance and phonological awareness were examined using phonological awareness tasks equated for cognitive demand across the levels of syllable, rime and phoneme, would the same pattern of findings hold?

With regard to the Dietrich and Brady (2001) study:-

If stability of naming performance was explored in children, both in the short term as well as over the course of a few years, how would dyslexic children compare to their also-developing control peer groups?

It is around these questions that the empirical experiments of chapter 5 are based. Before this, however, chapters 3 and 4 discuss how our current knowledge of phonological representation development, as outlined in chapter 1 can be integrated with what we now understand about the phonological representation deficit in dyslexia. This integration is discussed firstly with respect to the role of lexical growth, in chapter 3 and secondly with respect to the perceptual precursors of this lexical growth, in chapter 4.

Chapter 3 – Lexical influences upon phonological representation specificity

3.1 Introduction

Chapters 1 and 2 have explored what we know about the nature of phonological representations in typical development, as well discussing the hypothesis that in developmental dyslexia phonological representations are underspecified. This underspecification, presumed subtle, has the most detrimental consequences when phonological representations are employed in demanding operations such as phonological awareness tasks and literacy.

A resultant question is *why* the phonological representations of dyslexic individuals are underspecified. To answer this question it is important to understand the typical developmental timeline of phonological representation establishment, to see whether dyslexic children follow the same progression. In chapter 1 it was argued that initial phonological representation establishment appears to occur by the end of the first year of life. An important precursor to this is the child's ability to abstract phonological information from the speech stream in order to allow word segmentation, using prosodic cues such as syllable stress and accent, as well as statistical phonological regularities. As soon as the child begins to mentally represent words, however, the inherent properties of this mental lexicon are presumed to become increasingly important. The further development of phonological representations to a degree of specificity upon which conscious operations can be employed may thus depend on lexically-centred factors. Significant factors are thought to include word familiarity and the number of similar sounding neighbours a word has. This latter factor, also known as phonological neighbourhood density, has been relatively under-researched in comparison to word familiarity, both in accounts of typical and atypical development. Given its phonological nature, it was felt important within this thesis to understand the role of phonological neighbourhood density more clearly and so the empirical experiments of chapter 6 are designed to address this shortfall. In the current chapter we review what is already known about the role of lexical factors in both typically developing as well as dyslexic individuals. The review commences with studies looking at word familiarity. Attention then focuses upon studies examining the role of phonological neighbourhood density and resultant research questions are formulated.

3.2 Word familiarity and phonological representation

Word familiarity encompasses at least two constructs: age-of-acquisition (AoA) and frequency of exposure. Conceptually, there is a clear distinction between these constructs. A child, for example, may learn the name of a cartoon relatively early in life, yet this name may not have a high spoken frequency. Conversely, a dentist may be exposed to the word 'denture' very frequently in the course of their job, yet this is unlikely to have been a word that the dentist acquired at a young age. AoA and word frequency are also measured in quite different ways, with AoA usually estimated from subjective rating scales and word frequency estimated from objective word counts. In reality, however, there is a lot of overlap between the two and their separate influences upon language processing are often hard to determine. It is not an aim of this review to try and disentangle the respective influences of word frequency and AoA, but rather to typify how they affect processing tasks which require access to phonological representations.

In examining this issue there is a clear consensus, in both typically developing children as well as adults, that words with an early AoA/high spoken frequency show processing advantages across a range of tasks. Such tasks include spoken word recognition (e.g. Walley & Metsala, 1990, 1992; Metsala, 1997a) picture naming (e.g. Leonard, Nippold, Kail & Hale, 1983; Kirk, 1992, Troia, Roth & Yeni-Komshian, 1996; Swan & Goswami, 1997a, Nation, Marshall & Snowling, 2001), word list recall (Hulme, Roodenrys, Schweickert, Brown, Martin & Stuart, 1997) and phonological awareness (Metsala, 1999). When comparing performance effects caused by manipulations of word familiarity[2] between dyslexic and typically-developing children very similar effects are seen, although the disadvantage conferred by low frequency/late-acquired words is commonly reported as being augmented in dyslexic groups, across both recognition and production tasks (e.g. Gallagher, Frith & Snowling, 1999; Snowling, Goulandris, Bowlby & Howell, 1986; Swan & Goswami, 1997).

3.3 Phonological neighbourhood density and phonological representation

Phonological neighbourhood density is a more recently-considered lexical factor. It also appears to exert slightly more complex and interactive patterns of influence than word familiarity. Phonological neighbours are words that sound similar to each other. The number of phonological neighbours of a given (target) word is often operationalised as the number of words generated by the addition, deletion or substitution of one phoneme to the target (Luce, Pisoni & Goldinger, 1990). The idea that phonological neighbourhood density may affect phonological processing is derived from recent models of adult spoken word recognition, notably the Neighbourhood Activation Model (NAM; Luce & Pisoni, 1998).

3.3.1 The Neighbourhood Activation Model (NAM) and phonological neighbourhood density effects in adulthood

Many models of adult spoken word recognition now exist (e.g. Marslen-Wilson, 1989; McClelland & Elman, 1986; Norris, 1994) and common to all is the idea that a given word is recognised in the context of other words in memory, or is discriminated from various lexical alternatives. Fundamental to the NAM is the idea that when spoken words are recognised, speed and accuracy of target word recognition depends upon the number and degree of confusability of words that overlap with the target.

[2] Most studies report a manipulation of word frequency, perhaps partly due to the more comprehensive databases available for this variable in comparison to AoA. However, inspection of stimuli lists where given strongly suggests that the manipulation of word frequency has resulted in a similar AoA manipulation.

Word recognition thus occurs in the context of phonologically similar words activated in memory, and not just similarity in word-initial terms, which then *compete* for recognition. A word within a sparse phonological neighbourhood and so with few similar-sounding competitors will therefore be retrieved more quickly and accurately than a word within a dense neighbourhood (Luce & Pisoni, 1998; Vitevitch & Luce, 1998; 1999). More recently Vitevitch and colleagues have also attempted to explain findings from speech production studies using the neighbourhood activation idea. For speech production neighbourhood density appears to confer a facilitatory advantage, with a word in a sparse neighbourhood retrieved less quickly and accurately than a word in a dense neighbourhood (Vitevitch & Sommers, 2003). Vitevitch et al. posit that the activation of many phonologically-related primes in a dense neighbourhood will act to facilitate output processing, resulting in more rapid output performance.

Thus we can observe a pattern of phonological neighbourhood density inhibitory effects in speech recognition and facilitatory effects in speech production. When you manipulate phonological neighbourhood density however, you also manipulate an associated but distinct variable, that of phonotactic probability. Phonotactic probability refers to the relative frequencies of segments and sequences of segments in syllables and words (Vitevitch & Luce, 1999). Certain segments, such as word initial /s/ and sequences of segments such as /sʌ/ are more common than other segments, such as /j/, and sequences of segments such as /ji/. High phonotactic probability and neighbourhood density overlap to a large degree (Vitevitch, Luce, Pisoni & Auer, 1999), however, in studies where the two have been separated (through the construction of carefully controlled nonwords) contrastive effects have been observed. Whilst a dense phonological neighbourhood is facilitatory in production, but inhibitory in recognition, the effects of high phonotactic probability appear almost exclusively facilitatory (Vitevitch & Luce, 1999).

Vitevitch and colleagues have attempted to square this contradiction through a refinement of their earlier Neighbourhood Activation Model (Vitevitch, Luce, Pisoni & Auer, 1999). They posit that the differing effects are not incompatible and may depend upon the degree of mental lexicon involvement in any given task. For tasks relying heavily on stored lexical knowledge, such as deciding whether or not a presented stimulus is a real word or not, neighbourhood density characteristics will have a more important influence upon processing. When a task requires less reference to known lexical items, for example a same-different judgement task where stimulus items differ by one phoneme, the variable of phonotactic probability will be more influential. This proposition is backed up by empirical work carried out by Vitevitch and colleagues (Vitevitch & Luce, 1999). Research by Roodenrys and Hinton (2002) has also looked at the separable effects of phonotactic probability and neighbourhood density in a nonword serial recall task. These authors found that when phonotactic probability and neighbourhood density were manipulated separately, only neighbourhood density had a significant effect on recall performance, with items from dense neighbourhoods recalled more accurately than those from sparse neighbourhoods. Although nonwords were used in this experiment, the authors attributed the neighbourhood effects to evidence for the role of redintegration in serial recall (Schweickert, 1993), with stored lexical knowledge purported to help in maintaining the echoic memory trace of the presented nonword lists.

To summarise the adult literature concerning the role of phonological neighbourhood density and phonotactic probability in lexical processing, empirical evidence suggests that the more a task relies upon stored lexical knowledge, the more clearly the effects of phonological neighbourhood density are seen. The exact nature of these effects varies depending upon the demands of the task, with recognition processes inhibited by dense phonological neighbourhoods, and more active output processes facilitated by density.

3.3.2 Phonological neighbourhood density effects in childhood

As with the adult studies, the effects of both phonotactic probability and phonological neighbourhood density have been studied in children.

Studies looking at the effects of phonotactic probability in typically-developing infants and children have found high phonotactic probability processing advantages mirroring the adult findings. This advantage has been observed in infants as young as 9 months through preferential listening behaviours (Jusczyk, Luce & Charles-Luce, 1994) as well as in older children through tasks as diverse as new word learning (Storkel, 2001; 2003) and serial recall (Gathercole, Frankish, Pickering and Peaker, 1999).

Also mirroring the adult studies is a more complex picture of results for the effects of phonological neighbourhood density. One study that has examined these patterns in depth is that of Garlock, Walley and Metsala (2001). Garlock et al. explored the effects of neighbourhood density and its interaction with word familiarity (both word frequency and age-of-acquisition) across preschoolers, school-age children and adults using two spoken word recognition tasks: word repetition in noise and speech gating. In a speech gating task increasing amounts of acoustic-phonetic input from word onset are presented to the listener, who must try and guess the target word. The authors found clear developmental differences in the effects of neighbourhood density. In adults competition effects were seen in both word repetition and gating, thus items from sparse phonological neighbourhoods, with few 'competitors' were recognised more easily than those from dense neighbourhoods. For the gating task the school age children (≅ 7 years of age) showed similar effects, whilst the preschool children (≅ 5 years of age) showed no performance effects of neighbourhood density. For the word repetition task, all groups showed a sparse neighbourhood repetition advantage, however an interesting group x AoA x neighbourhood density interaction also occurred. For adults the sparse neighbourhood advantages were similar for early versus late-acquired words, for the school age children the advantage was larger for early vs. late-acquired words whilst in the youngest group the advantage was only present in the early-acquired words. From these findings it can be supposed that in childhood early acquired words have better established lexical, and thus phonological, representations. Once established, it appears that the collective properties of phonological representations then have the power to influence subsequent phonological processing. The study of Coady and Aslin (2003) is also of note here. These authors carried out an analysis of the expressive lexicons of two young children (age 3;6) and found that the lexicons of these children were phonologically denser than those of adults. This suggests that phonological neighbourhood density may be important from an earlier age than previously thought, although it is not until later that robust evidence of its processing influence are observed.

Studies have also looked at the effects of phonological neighbourhood density in phonological awareness tasks. Metsala (1999), for example, found that 3-4 year old children could perform a phoneme-blending task more accurately for words from dense as opposed to sparse phonological neighbourhoods, whilst De Cara and Goswami (2003) reported a similar pattern of results for 5 year old children with a rhyme judgement task. This pattern also matches the facilitatory effects of dense phonological neighbourhoods seen in adult studies involving more active output processing.

Together these studies provide very exciting evidence concerning the dynamic nature of the developing lexicon and the effects of lexical growth upon activities which depend on access to phonological representations. It appears that whilst the influence of phonotactic probability can be observed from earliest infancy, the influence of phonological neighbourhood density only becomes apparent once lexical, and thus phonological representations have become well-established. This makes phonological neighbourhood density a particularly interesting factor with regard to developmental dyslexia, where we are positing through the Phonological Representations Hypothesis that something has gone awry in this process of phonological representation establishment. Two further studies are of particular relevance in this regard and are described in the next section.

3.3.3 Phonological neighbourhood density effects in developmental dyslexia

In a study by Metsala (1997b), the spoken word recognition of thirty-nine school age dyslexic children was assessed using a speech gating paradigm; both word frequency and phonological neighbourhood density were systematically varied. In terms of overall performance, the dyslexic children required more speech input in order to correctly identify target words. A main effect of frequency was observed, favouring higher frequency target words and there was no group interaction for this result. The phonological neighbourhood density manipulation yielded a more complex pattern of results. Although there were no significant group differences for the identification of target words from dense phonological neighbourhoods, when targets were from sparse neighbourhoods, the dyslexic children required significantly more speech input than their typically-developing peers to achieve correct identification.

Metsala interpreted this finding as suggesting that for the dyslexic children, their phonological representations of words from sparse phonological neighbourhoods remain overly 'holistic' in nature. This conclusion draws very much from the ideas of the Lexical Restructuring Hypothesis (Walley, 1993), in which vocabulary growth and the proliferation of phonological neighbours are thought to be key drivers of fine-grained phonological representation. Metsala thus suggested that in dyslexia, this process has been interrupted. In a speech gating task, when identification performance relies upon phonological representations from sparse neighbourhoods, which may be relatively underspecified anyway, particular difficulties arise.

Such a conclusion appears justified. However, closer inspection of the results raises important questions. Notably, when the group performances for targets from dense versus sparse neighbourhoods are studied, it appears that the group x density interaction arises not through a relative decrement of performance in the dyslexic group for sparse neighbourhood targets, but rather, a relative performance advantage for these targets over their dense neighbourhood counterparts in the control group. In comparison, the performance of the dyslexic group for dense and sparse neighbourhood targets appears approximately equal. Although not discussed within the published article, this would appear to be an important theoretical distinction.

A subsequent study offers some evidence in this regard. Roodenrys and Stokes (2001) examined serial recall performance in 7-9 year old dyslexic children alongside chronological and reading level matched controls. Phonotactic probability was the factor manipulated in this study, however neighbourhood density was not controlled and in a subsequent paper Roodenrys and Hinton (2002) show empirically that effects attributed to phonotactic probability in serial recall may in fact be driven by neighbourhood density effects (high phonotactic probability correlates with dense phonological neighbourhoods). The influence of neighbourhood density is possible through the importance of long-term lexical knowledge in 'redintegration' or the reconstruction of decaying traces in phonological short-term memory recall (Gupta & MacWhinney, 1997; Hulme, Maughan & Brown, 1991; Hulme, Roodenrys, Schweikert, Brown, Martin & Stuart, 1997; Schweikert, 1993). Roodenrys and Stokes found that although the dyslexic group were performing more poorly than their age-matched peers, the facilitatory effect of high phonotactic probability was similar across groups. If phonological neighbourhood density was playing a role in this result, this would suggest that dyslexic children are sensitive to such phonological factors within their lexicon. Clearly replication of these results with stimuli sets specifically manipulated for neighbourhood density is needed.

3.4 Summary and Research Goals

From the information here it is clear that phonological neighbourhood density is an under-researched lexical factor with high relevance to the study of developmental dyslexia. From research carried out with typically developing children there is evidence that the effects of phonological neighbourhood density upon lexical processing may only emerge once lexical representations are well-established and thus it may act as a sensitive marker of developmental change. Initial findings investigating phonological neighbourhood density in dyslexic children are as yet inconclusive. It is possible that dyslexic children do not show processing effects of phonological neighbourhood density, suggesting a cognitive difference at the level of higher-order phonological organisation. A further possibility is that the phonological representations of dyslexic children are not responding as efficiently to neighbourhood density pressures for greater specification. This may be most noticeable for representations already residing in sparse neighbourhoods, where the development of adequate specificity for phonological processing across diverse conditions may become unduly delayed. The experiments described in chapter 6 attempt to differentiate between these possibilities.

Chapter 4 – Auditory perceptual influences upon phonological representation specificity

4.1 Introduction

In thinking about dyslexia and the Phonological Representations Hypothesis, the focus of the previous chapters has been upon the link between literacy problems and abstract cognitive deficits in the establishment of phonological representations. Abstract phonological processing does not occur in a vacuum however, and relies upon a raw substrate of sensory input such as acoustic speech signals. The transformation of such input into information available to higher level processing is the act of perception. With the question remaining of why phonological representations are underspecified in dyslexia it is logical to look to perceptual processing for possible causal mechanisms.

The last decade particularly has seen an explosion of studies looking for perceptual processing differences in dyslexia, in auditory, visual and other sensory domains. Although there is a resultant consensus that perceptual differences do exist, their pervasiveness and causal role are much debated. The most convincing evidence exists for auditory perceptual differences and it is this sensory modality investigated here. The chapter is divided into two sections. Firstly there is a review of the key research findings concerning behaviourally-observed auditory processing differences in dyslexia. The second section then reviews neurophysiological findings as this is a research tool also used in the current thesis.

4.2 Behavioural investigation of auditory processing in dyslexia

Most behavioural studies of auditory processing in dyslexia have focused their attention upon auditory parameters that signal phoneme-size, or 'segmental' distinctions, for example rapid frequency transitions (Tallal, 1980; Reed, 1989; Mody, Studdert-Kennedy & Brady, 1997; Waber, Weiler, Wolff, Bellinger, Marcus, Ariel, Forbes & Wypij, 2001). Such studies thus form the initial basis for discussion.

However, it is the position taken here that in thinking about dyslexia as a developmental difficulty, we should be looking at auditory parameters of salience when infants are initially establishing phonological representations. As mentioned in chapter 1, in the first year of life syllable rhythm and stress are important cues to word segmentation. These cues operate over larger time windows than those at the phoneme level and are thus 'supra-segmental'. The chapter thus proceeds by describing the few studies that have examined supra-segmental auditory perception in dyslexia. A new candidate mechanism is then proposed in the light of the current knowledge and the explanatory power of this candidate tested in chapters 7 & 8.

Although in existing studies of both segmental and supra-segmental auditory perception in dyslexia both adults and children have participated, little consideration has been given to the nature of developmental maturation in auditory perceptual skill (though note McArthur & Bishop, 2004, for attention to developmental picture in SLI). We know that in normal development auditory processing skills such as frequency discrimination and temporal resolution continue to develop even during late childhood (Fischer & Hartnegg, 2004; Wightman, Allen, Dolan, Kistler & Jameison, 1989) and so the auditory processing of adults will be different to that of children. As the study population in this thesis is school-age children and for reasons of space, unless otherwise stated the studies referred to here focus upon children. The only exceptions to this are where very few studies are available concerning a particular auditory parameter.

There are also very few studies that feature a reading level-matched control group. In one study exploring performance on a rapid auditory processing task (see sections 4.2.1-4.2.2), Marshall, Bailey and Snowling (2001) reported that the dyslexic group (mean age of 12 years old) performed at an equivalent level to their reading-level matched peers. In a further study, looking at speech sound categorisation on a /b/~/p/ continuum, Manis, McBride-Chang, Seidenberg, Keating, Doi, Munson and Petersen (1997) found that although at a group level, the dyslexic group appeared to perform similarly to their reading-level matched peers in the categorisation task, if the dyslexics were sub-divided according to their phonological awareness ability, the group with better phonological awareness skills could categorise sounds at the level of their age-matched peers, whilst the poor phonological awareness group performed worse than both control groups. Taken together, these results suggest that the relationship between auditory processing, phonological awareness and resultant reading level is a complex one and that more widespread inclusion of reading-level matched control groups is important. For this reason, a reading-level matched control group is used in the experiments reported here.

4.2.1 Evidence for auditory perceptual processing in developmental dyslexia at a segmental level: the Rapid Auditory Processing Deficit Hypothesis

As early as 1937, through the studies of Orton (1937), links were being made between children's literacy difficulties and more basic perceptual anomalies. It was not until Tallal's key study of 1980, however, that the idea of sensory processing, and specifically auditory sensory processing as a causal factor in dyslexia really took off. Using a paradigm developed in her studies of children with Specific Language Impairment (Tallal & Piercy, 1973) Tallal's investigation centred around temporal order judgement (TOJ), through an activity known as the Repetition Task. In this task, two sounds were firstly presented in isolation, and the listener learnt to respond differentially to these sounds by pressing one of two buttons. Following this training phase the sounds were then presented in pairs, at varied inter-stimulus intervals (ISIs), and the listener was asked to press the associated buttons in the order heard. The same stimuli were also presented in a same-different judgement paradigm.

In a study involving dyslexic children, Tallal (1980) showed that whilst at long ISIs ($\geq$428ms) all the children performed at or near ceiling, at shorter ISIs ($\leq$305ms), whether in the Repetition Task or same-different judgement format, 8 out of the 20 dyslexic children demonstrated performance deficits. Parallel studies of children with SLI (Tallal & Piercy, 1973) showed widespread difficulties for this group of children in short ISI ($\leq$150ms) conditions. In a further study of children with SLI using speech sounds (Tallal & Piercy, 1974), it was found that the SLI children had greater difficulty than their controls in discriminating between /ba/ and /da/, stimuli differing only in the frequency of formant transitions between the consonant and vowel, occurring over the course of approximately 40ms. Taking these findings as a whole, it was concluded that both groups of children evinced an auditory deficit specific to the perception of rapidly changing or brief sounds. Given that discrimination of many phonemic contrasts without context depends upon the ability to process frequency formant transitions and voice onset times occurring within very brief temporal 'windows', the accompanying assumption was that difficulties in discrimination at this level might lead to degraded phonological encoding. In the dyslexia study (1980), the high ranked correlations (Spearman's rho = 0.81) between the number of errors made in a phonics reading test and the number of errors made in responding to the rapidly presented stimuli in the auditory perceptual tasks was taken as evidence to support this supposition, suggesting that a basic perceptual mechanism may compromise the development of stable phonological representations, which in turn leads to the phonological processing and literacy difficulties observed in dyslexia. This viewpoint has become known as the 'Rapid Auditory Processing Deficit (RAPD)' Hypothesis.

Although significant in their own right, over the last decade the impact of the findings related to the RAPD hypothesis has been augmented by subsequent developments. Firstly, and directly linked to these study findings has been the development by Tallal and colleagues of a computer-based remediation programme, 'Fast ForWord', claiming quite remarkable results in terms of remediating both language impairment and reading delays (Tallal et al., 1996; Scientific Learning Corporation, 2004). Motivated in part by findings that speech stimuli with lengthened transitions were much better discriminated by children with SLI (Tallal & Piercy, 1975) the programme uses an 'enhancement' algorithm, which claims to make natural speech more intelligible for these children through both lengthening the most critical information-carrying parts of the speech stream as well as altering the amplitude properties of the speech envelope. As the importance of a literate society increases, apparently positive results arising from a remediation programme varied in its levels of speech and language focus have prompted much research interest from the wider academic community. Studies have questioned the efficacy of the Fast ForWord programme over more traditional phonological-awareness based interventions, as well as challenging the role of the rapid auditory processing part of the training (e.g. Hook, Macaruso & Jones, 2001). Further studies have examined this latter challenge in greater depth, attempting to better understand which auditory parameters, if any, are of most importance to reading success.

4.2.2 Challenges to the RAPD Hypothesis I: Is the auditory processing deficit of dyslexics confined to rapidly presented or brief auditory input?

A major claim of Tallal's original 1980 study was that dyslexic children have a specific difficulty with the processing of rapidly presented or brief acoustic stimuli. This has also perhaps been one of the most clearly refuted arguments as well, through a number of converging sources. Most directly, several studies have attempted to replicate Tallal's original findings in using the Repetition Task with dyslexics. The first replication was by Reed (1989), who did in fact obtain supportive results, extending Tallal's findings of tone temporal order judgement difficulties to an equivalent deficit in consonant-vowel (CV) ordering in 8-10 year old children with reading difficulties. However, looking more closely at these results, as well as more recent positive replications (e.g. De Martino, Espesser, Rey & Habib, 2001; Rey, Martino, Espesser & Habib, 2002; Heiervang, Stevenson & Hugdahl, 2002) it becomes clear that the use of a non-adaptive presentation format consistently yields ceiling effects for control groups and the lack of reliability and sensitivity in comparison to the now readily-available adaptive psychoacoustic procedures calls into question the reliability of these findings. As well as these methodological issues, other replications have failed to find relationships between nonverbal temporal processing and phonological skills or reading (Farmer & Klein, 1993). In addition, other studies have found that as long as performances at long inter-stimuli intervals are not at ceiling, the difficulties dyslexic children demonstrate are not limited to the short ISIs alone (Marshall, Snowling & Bailey, 2001; Nittrouer, 1999; Reed, 1989; Waber, Weiler, Wolff, Bellinger, Marcus, Ariel, Forbes & Wypij, 2001) and in fact a study where the Repetition Task was applied to children entering school (Share, Jorm, MacLean &

Matthews, 2002), it was only at long ISIs that those later identified as having reading difficulties differed from those who went on to read normally. As a final point here, there have also been a number of findings where other tasks involving 'rapid' auditory processing have not yielded performance differences between dyslexic children and their controls, for example, detection of short tones following a masker (forward masking; Rosen & Manganari, 2001), whilst as discussed in section 4.2.5, studies examining 'non-rapid' auditory phenomena, such as detection of amplitude modulations occurring at rates as low as 4Hz have found robust group differences (Lorenzi, Dumont and Füllgrabe, 2000).

4.2.3 Challenges to the RAPD II: Is the auditory processing deficit of dyslexics specific to speech?

This issue remains a more controversial area of debate. The original findings of Tallal centred upon performance in a non-speech temporal order judgement task and although not directly tested by Tallal and colleagues, the assumption was that this non-speech deficit would directly relate to difficulties in the temporal ordering of speech sounds, required for successful literacy acquisition. The study by Reed (1989) extended Tallal's original findings with dyslexic children by showing deficits in the ability to process speech sounds differing only in the rate of formant transition within a similarly brief time window, though disappointingly the relationship between non-speech and speech deficits was not directly tested.

The next significant episode in answering this question was precipitated by the study of Mody, Studdert-Kennedy and Brady (1997). This study involved a group of poor readers who were also selected on the basis of poor discrimination performance in a synthetic speech task involving the phonetically similar syllables /ba/ and /da/. Of note, however, was that Mody et al. found no deficit for these children in discriminating between carefully-created non-speech analogues of these stimuli, critically featuring the same second and third formant transitions, assumed to be the acoustic signature of the dyslexic children's difficulties which would accordingly link speech and non-speech findings. In 2001, Serniclaes, Sprenger-Charolles, Carré & Demonet also carried out a deficits is only about 40%. An associated debate in this regard is how much language ability correlates with reported auditory deficits, with some authors suggesting that auditory deficits are restricted to those dyslexic individuals who also have additional language impairments (Heath, Hogben & Clark, 1999; McArthur & Hogben, 2001).

But rather than write off the studies to date as a well-intentioned, but essentially misguided search for an elusive causal factor, it could be that we have not yet looked in the right place. Many studies have looked at the particular difficulties dyslexic children have with phonemic awareness and so in their search for underlying auditory processing difficulties, the focus has also been at this level – indeed, Tallal's 1980 study typifies this approach well. However, as discussed in chapter 1, explicit phonemic-level representation is part *product* of learning to read an alphabetic script. If constituting a psychological entity not necessary for speech perception and production, then perhaps we should be looking at the auditory correlates of developmentally more primary levels of representation.

Thinking back to chapter 1, when discussing the initial establishment of phonological representations in the first year of life, the importance of perceptual cues operating at grain-sizes larger than individual phonemes was highlighted. The role of phonotactic probability was discussed as a cue to segmenting the speech stream and sensitivity to this has been shown in infants as young as 7 months (Mattys, Jusczyk, Luce & Morgan, 1999). At the same time, infants between 6 and 9 months of age have been shown to be sensitive to the predominant stress pattern of words in their native language (Jusczyk, Cutler, & Redanz, 1993) and so just as evidence of explicit phonological awareness starts with the awareness of large units such as syllables, so infant's initial phonological perception biases appear to begin with awareness of more holistic speech stream features such as syllable timing and sequential probability. Units within speech that are 'above' the phoneme in terms of phonological structural hierarchy can also be described as 'supra-segmental'.

A number of recent studies have started looking at dyslexics' sensitivity to auditory features operating over longer temporal windows such as these, at a supra-segmental level, and so the key findings to date will be summarised below. Because the number of studies in this area can not yet rival those exploring segmental auditory processing phenomena, evidence from both adults and children will be considered.

4.2.5 Evidence for auditory processing deficits in developmental dyslexia at a supra-segmental level

Sensitivity to phonological information present at a supra-segmental level, is dependent not upon the ability to distinguish subtle phonemic contrasts, but rather appreciation of the overall modulations of the speech stream, or the 'temporal envelope' of speech. The speech signal contains modulations of both frequency and amplitude, both of which can occur at varied rates. The modulations signalling syllable-level information are generally believed to be *amplitude* modulations below 4 Hz (i.e. a modulation rate of less than 4 cycles per second; Houtgast & Steeneken, 1985; Drullman, Festen & Plomp, 1994). Shannon, Zeng, Kamath, Wygonski & Ekelid (1995) have also shown that amplitude modulation at these low rates, as opposed to spectral frequency cues, is the critical factor determining speech intelligibility for adult listeners.

A handful of studies have explored amplitude envelope perception in dyslexic individuals. In order to ensure that only the acoustic cue of interest is being varied, e.g. amplitude modulation frequency, researchers have largely confined their studies to those involving simplified non-speech stimuli. This allows very specific acoustic manipulations to be achieved. The majority of studies have also used a two-interval forced choice detection paradigm. In this paradigm two sounds are presented, one containing a sound modulation, the other not; the listener's task is to decide which sound contains the modulation, whilst an adaptive threshold procedure gradually reduces the perceivable difference between the sounds to find the individual's 'detection threshold'. In a study by Menell, McAnally & Stein (1999) the amplitude modulation ('AM') detection thresholds for a group of dyslexic adults measured between 10 and 320Hz were significantly higher (i.e. poorer) than normally reading controls at most rates. There was also a significant correlation between behavioural AM detection threshold and reading speed and accuracy. In the same study Menell et al. also recorded neurophysiological responses to amplitude modulated noise (10-160Hz) in both the dyslexic and control groups, finding a behaviourally-associated reduction in the amplitude-modulation-following-responses (AMFRs, a cortical or thalamic neural response; see section 4.3.6) of the dyslexic group at every measured rate.

A further study by Witton, Stein, Stoodley, Rosner & Talcott (2002) showed a more mixed picture, with the adult dyslexics significantly less sensitive than controls to the presence of 20Hz AM, though similarly sensitive at the lower rate of 2Hz. Auditory thresholds for the 20Hz AM detection task also predicted significant and independent variance in pseudoword reading accuracy, beyond that accounted for by other cognitive skills. Although processing of slow rates of amplitude modulation has different underlying mechanisms to those of frequency modulation (Hartmann, 1997), Witton et al.'s study also examined sensitivity to frequency modulation at 2Hz and 240Hz. The dyslexics again showed differential performance effects to their controls, though this time they were equally sensitive at the higher rate of 240Hz FM, with less sensitivity evident at the 2Hz FM rate. Witton et al. refer to basic psychoacoustic research which posits that at high rates of frequency/amplitude modulation, detection (e.g. 240Hz) is achieved by non-temporal mechanisms, which may in part explain the performance difference in this case. With respect to the varied amplitude modulation findings Witton et al. conclude that whilst further research is clearly warranted, the deficit dyslexic individuals have in detecting amplitude modulation is not a generalised one, but rather specific to certain modulation rates.

Only two studies to date have examined amplitude modulation sensitivity in dyslexic children. In the first of these, Lorenzi, Dumont and Füllgrabe (2000) examined AM detection thresholds in 8-14 year old children with dyslexia (n=6). They found that the detection thresholds of dyslexic children at 4 Hz particularly, but also 1024 Hz, were much higher than for a group of normally-reading control children, as well as a group of normally-reading adults. They found no difference between groups in the detection of 16, 64 or 256 Hz AM. Interestingly, the normally-reading child and adult groups did not differ significantly from one another in any of their detection thresholds, supporting the idea that AM detection is an auditory ability that is used and so stabilised at a developmentally early stage. In this study Lorenzi et al. also looked at the dyslexic children's ability to identify synthetically manipulated speech sounds in which the spectral information was degraded, leaving predominantly amplitude envelope information. Here both the normally-reading and dyslexic children performed more poorly than the normally-reading adults, however whilst the normally-reading children showed an improvement in performance across sessions, the dyslexic children did not. These findings suggest that whilst typically-developing children acquire basic sensitivity to amplitude modulation early on, sophisticated usage of this in speech decoding is not immediately adult-like, and undergoes refinement. For dyslexic children, in whom basic amplitude modulation detection is weaker, the act of using this information in speech decoding will be considerably more difficult and so a performance gap between themselves and their peers will occur.

In a second published study Lorenzi et al. attempted to both replicate these findings, but also to extend their investigation to the measurement of AM *discrimination*, as well as just detection (Rocheron, Lorenzi, Füllgrabe & Dumont, 2002). Whilst detection tasks necessitate being aware of a modulation within a sound as opposed to no modulation, discrimination tasks use supra-threshold degrees of modulation and require the listener to distinguish between modulations of varying depth or rate. Assessing 10-15 year old children with both 4 and 128Hz AM stimuli, the authors found higher detection thresholds for the dyslexics (n=10) at both modulation frequencies, though again the deficit was strongest at 4Hz in the detection task. In terms of discrimination performance, the main group differences occurred for the 128Hz AM condition. The dyslexic children did not differ significantly from the controls in an intensity discrimination control task using the same experimental presentation, thus ruling out procedural reasons for the group differences. This second study convincingly replicates the 4Hz AM detection deficit within the dyslexic group. However, it also leaves loose ends. One such unanswered question is why detection deficits were present to some degree at 128Hz, with the findings of the first study not predicting difficulties at this rate. A further question is how the detection and discrimination results fit together. The authors do make hints to this end, suggesting that reduced audibility of temporal envelope cues, as measured by the detection thresholds, in effect 'smooth' the incoming auditory representations, whilst poor encoding fidelity, as measured by the supra-threshold discrimination weaknesses, result in reduced information-carrying capacities for the information within the envelopes.

Current findings with regard to dyslexia and auditory perceptual processing at the level of the temporal speech envelope thus suggest reduced AM detection sensitivity in both children and adults, with perhaps the most convergent findings emerging for the lower modulation rates characteristic of speech (Lorenzi et al., 2000; Rocheron et al., 2002). Links have been hypothesised between modulation salience, resultant intelligibility of phonological information within the speech stream and the ultimate quality of the phonological representation achievable but no cohesive explanatory framework currently exists. In the section below a testable hypothesis is thus introduced.

4.2.6 Amplitude envelope onsets and developmental dyslexia: a new hypothesis

Being able to detect amplitude modulations will allow one to attune to the basic rhythm of the speech stream, determined by the presence of syllables. This is crucial in allowing subsequent fine-grained sub-syllabic analysis to occur. As in music, speech rhythm, or tempo, provides the scaffolding structure within which more 'micro' acoustic information is carried (Fraisse, 1963). In dyslexic individuals, despite the slightly mixed results, it appears that there is a reduced sensitivity to this basic amplitude modulation structure. It also appears that this deficit is not restricted to rapid amplitude modulation changes, but rather the strongest results so far implicate modulation detection ability when the modulation rate is slow, i.e. when amplitude is changing relatively slowly as a function of time. This suggests that dyslexic individuals have difficulty processing auditory information when the dynamic information provided by the signal as a function of time is *reduced.* This hypothesis is quite different to the early ideas of researchers such as Tallal (1980), who have espoused the view that when dyslexic individuals are faced with a lot of changing acoustic information within a short time window, they manifest processing difficulties. However, the two hypotheses are not mutually exclusive. In thinking about amplitude fluctuations, the changes occurring over time are overall acoustic energy changes. This is distinct to the frequency, or spectral changes investigated by Tallal and colleagues. We know that frequency discrimination skills have a long maturational course and that spectral information is important for identifying fine-structure within speech. We also know that speech perception in general is a dynamic process and that as children develop, the perceptual weighting of cues such as noise spectra vs. formant transitions, employed in phoneme identification, appears to change (Nittrouer & Miller, 1997). Therefore, when the auditory skills of school-age children are investigated, if we assume that dyslexic children may have manifested auditory processing differences from earlier in development, some 'downstream' effects on a wider range of auditory abilities, such as frequency discrimination could be predicted. In terms of identifying the earliest locus of deficit, however, it is the hypothesis put forward here that we must first understand more about amplitude envelope processing.

Taking the idea of acoustic energy change over time a step further, within any amplitude modulation cycle, as well as the overall length, an individual cycle can vary in how quickly the maximum amplitude is reached, its amplitude rise time, as well as how rapidly it decays. The variation this introduces, especially in terms of rise times, has important linguistic consequences. As well as acting as a segmental cue to manner of articulation, for example the voiceless affricate-fricative distinction (/tʃ/ and /ʃ/ as in the initial consonants of 'chop' and 'shop'; Howell and Rosen, 1983), amplitude rise time is also used in syllabification (Mermelstein, 1975 cf. Rosen, 1992) and the demarcation of linguistic units (vowel, syllable or word; Rosen, 1992). This latter role is important when considering the segmentation task tackled by infants. The importance of amplitude rise times to speech processing has also been elaborated in the work of Scott (1993), who has shown through empirical research that amplitude envelope rise times in speech correlate with the vowel onset within any syllable.

4.2.7 The work of Scott (1993)

Scott's work attests to the importance of amplitude envelope onset (AEO) rise times in speech processing and is also of high relevance to the current thesis via the empirical methods used to show this. Scott's investigation examined AEO rise times as a possible index of perceptual centres, or 'p-centres' in speech. First described by Morton, Marcus and Frankish (1976), the term P-centre is used to describe the perceived moment of occurrence of a sound, either speech or non-speech. The need to describe such a phenomenon came from an intriguing observation made by Morton et al. In their study individuals were asked to align a spoken count sequence (i.e. a verbal recitation of the numbers "one, two, three...") so that it sounded regularly paced. What the researchers found was that it was not the physical onsets of the spoken words that were regularly spaced, but something more abstract, that appeared to give each word its 'beat'. Morton et al. were not able to identify an invariant acoustic feature that correlated with these 'beats'. Thus, in the following decade further attempts were made to pinpoint the acoustic substance of 'P-centres'. The resultant models tended to take a 'global' approach (Marcus, 1981; Howell, 1988), where it was assumed the whole signal was needed to determine P-centre location. Scott (1993) on the other hand argued that such thinking was at odds with models of musical 'perceptual attack', where perceptual moments of occurrence were attributed to discrete acoustic onset events (Vos & Rasch, 1981, cf. Scott, 1993; Gordon, 1987). Scott investigated this disparity empirically though a series of production and perception tasks. Productively, different speakers (healthy adult volunteers) were asked to produce spoken number sequences to a regular rhythm. Perceptually, similarly to Morton et al. (1976), a perceptual 'dynamic rhythm setting' task was employed. In this activity spoken numbers were presented asynchronously and using a potentiometer knob listeners were asked to alter the interval between the spoken numbers until they sounded regularly spaced. Applying a series of different mathematical models to the resultant data Scott concluded that the parameter determining rhythmicity in both cases was AEO rise time. Although not speech-specific, Scott further concluded that in speech stimuli, AEO rise time correlated with the vowel onset in any given syllable.

4.2.8 Summary of section 4.2

A clear message transmitted by section 4.2 is that behavioural studies of auditory processing in dyslexia have not yet reached a consensus concerning the loci of deficits, however it is clear that many hurdles to consensus exist, including varied assessment formats, diverse age ranges studied and different interpretations of the same results possible.

A novel idea put forward here is that perhaps, just as the previous chapters have looked to the earliest stages of representation establishment for cognitive level clues regarding the phonological deficit, we should also look to this developmental stage for perceptual clues. In this way it has been put forward that supra-segmental cues provided by the syllable rhythm may be important. Through being a perceptual cue that contributes towards first attempts at word segmentation and thus representation, a subtle deficit at this level could impact later levels of phonological representation specificity.

The findings of Scott (1993; 1998) offer an opportunity to focus such investigations. Firstly, this work isolates AEO rise time as a more specific parameter yielding the perception of a syllable's 'beat'. By linking AEO rise time to the characteristics of vowel onset, a more explicit role for this parameter in phonological processing can be hypothesised as compared to extant research. Accurate perception of the rise time of a vowel may, for example, help in the segmentation of the vowel from the surrounding consonants. Secondly, by empirically linking AEO rise times of both speech and non-speech sounds, new experimental paradigms are made possible for the exploration of AEO, or beat processing in dyslexic children. The translation of these ideas to a series of exploratory behavioural studies with school-age dyslexic children is described in chapter 7.

As well as behavioural study, AEO processing is also amenable to neurophysiological investigation. This is a non-invasive technique that can record superficial cortical activity in response to auditory stimuli and has the potential to inform us in much greater depth as to the level of conscious auditory processing occurring, as well as the time course and distribution of cortical responding. The next section of this chapter will describe the methodology of neurophysiological assessment in more detail, as well as summarising how the technique has already been used to investigate auditory processing in dyslexia.

4.3 Neurophysiological investigation of auditory processing in dyslexia

4.3.1 Neurophysiological assessment: Event-Related Potentials

Neurophysiological assessment is a very broad area of investigation. There is one particular methodology, however, that has particular relevance to the study of auditory processing in dyslexia. This is the recording of Event-Related Potentials (henceforth, 'ERP's). ERPs reflect the electrical voltage changes measurable on the scalp surface that correspond to the synchronised post-synaptic activity of neuronal populations at the cortical surface. These voltage changes are time-locked components, meaning they will occur within a consistent time-window immediately following an externally presented 'event', such as an auditory stimulus. They are computed through the comparison of the voltage emissions from cortical scalp electrode sites with a neutral reference electrode, such as one placed upon the nose. They can be extracted from the more general electroencephalography (EEG) waveform through signal averaging. By combining the ERP responses to many presentations of the same stimulus random cortical activity caused by other processing can be averaged away, leaving the specific pattern of response to that stimulus. The time-locked nature of these components means that millisecond recording resolution can be achieved and so the method is extremely useful for the study of auditory processing. The spatial resolution of the ERP recording, however, is much poorer than for magnetic resonance imaging (MRI) or magnetoencephalography (MEG). This is due to poor volume conduction through the brain, distortion by the skull and lack of signal from deep brain structures.

As well as the fine temporal resolution there are further advantages offered by ERP measurement. Firstly, brain responses to stimuli can be recorded whether or not the participant is actively attending. This overcomes the attentional/motivational loading that behavioural tasks can add to measurement of an auditory parameter of interest, especially when the study involves children with specific learning difficulties. Furthermore, although the stimuli and presentation format of sounds may vary, the performance variability caused by procedural demands is much reduced. Through the large number of ERP studies now amassed, we also now have a good understanding of certain typical voltage changes, called 'components', that occur in response to a range of stimuli; these can index levels of perceptual processing even before conscious responding and thus provide information not possible through traditional behavioural techniques.

One of these ERP components is called the 'N1' and is of particular interest here through its known sensitivity to stimulus amplitude rise times. A general overview of the N1 follows below. A further component, the Mismatch Negativity (MMN) is briefly introduced, as although not reported in this thesis, this is the component most studied in dyslexic samples to date.

4.3.2 The N1 Component

In auditory processing, the N1 component is the first of the so-called 'long latency' voltage changes. It is a negative voltage peak occurring approximately 100ms post stimulus onset and in comparison to earlier brain-stem auditorily evoked potentials (BAEPs) and the middle-latency responses of the primary auditory cortex, the N1 is the first event-related response to show stimulus-specific characteristics as well as evidence of *preservation* of stimulus-specific code – i.e. some form of stimulus encoding (Näätänen & Winkler, 1999). Although one main peak is visible, it is now understood that the N1 consists of many subcomponents which vary in their time course, topography and maturation (Näätänen & Picton, 1987).

In adulthood the most prominent subcomponent is the N1b. This subcomponent is recorded maximally at bilateral fronto-central electrode sites, with a probable generator within the supra-temporal plane of the auditory cortex. During childhood the

N1b has a more parietal distribution, shifting to the adult-like fronto-central pattern by the mid-late teenage years (Pang & Taylor, 2000).

A more robust N1 subcomponent in childhood is the N1a. This subcomponent typically occurs about 25ms before the N1b and is recorded maximally at the temporal electrode sites. A probable generator is thought to be the auditory association cortex in the superior temporal gyrus. This subcomponent is also bilaterally distributed, though hemispheric maturational differences are more obvious for this component than the N1b. Whilst the left hemisphere N1a is adult-like in form by 3 years, the right hemisphere matures around 7-8 years (Pang & Taylor, 2000).

4.3.3 The Mismatch Negativity (MMN) Component

Another ERP component extensively studied in both normal and special populations is that known as the Mismatch Negativity, or MMN. This component is elicited whenever an infrequent ('deviant') auditory stimulus is presented within the repetitive context of more commonly occurring 'standard' auditory stimuli. By presenting stimuli in this way, the so-called 'oddball paradigm', voltage changes to the standard and deviant stimuli can be compared and the brain's response to stimulus *change* thus indexed. This is distinct from the N1, which is a more *absolute* response to the onset or offset of a stimulus. The encoding indexed by MMN appears to be available to higher levels of cognitive processing and related to processes of echoic short-term memory (Cowan, Winkler, Teder, & Näätänen, 1993). When averaged responses to the standard stimuli are subtracted from those to the deviant stimuli a 'difference wave' is obtained. As with the N1, the MMN has more than one subcomponent, however the most studied response is the fronto-central negativity peaking at 100-250ms from stimulus onset, with probable generators in the right inferior frontal cortex, left superior frontal gyrus and cingulate. The MMN can be elicited by any discriminable change in some repetitive aspect of the ongoing auditory sequence (Näätänen, 2001) and is observed both for basic changes in e.g. frequency, duration or intensity as well as more abstract pattern changes within sound sequences, where the deviant is not always physically novel. In a study by Paavilainen, Simola, Jaramillo, Näätänen, and Winkler (2001), MMN was elicited when the standard was defined by the rule, the higher the frequency, the greater the intensity. Findings such as these suggest a very intimate coupling of top-down cognitive expectancies with low level perceptual processing. Developmentally, MMN-like responses have even been recorded in pre-term infants (Cheour, Leppänen & Kraus, 2000). During childhood, however, the MMN scalp distribution appears broader and more central than in adults and a gradual reduction in both the amplitude and latency of the response occurs (Gomot, Giard, Roux, Barthelemy & Bruneau, 2000). We also know that MMN correlates closely with behavioural performance in both normal and learning-disabled populations (Korpilahti & Lang, 1994; Kraus, McGee, Carrell, Zecker, Nicol & Koch, 1996).

4.3.4 The MMN and dyslexia

MMN to phoneme change (Schulte-Körne, Deimel, Bartling & Remschmidt, 1998; Schulte-Körne, Deimel, Bartling & Remschmidt, 2001; Maurer, Bucher, Brem & Brandeis, 2003) or more basic changes in frequency (Schulte-Körne et al., 1998; Baldeweg, Richardson, Watkins, Foale & Gruzelier, 1999; Schulte-Körne et al., 2001; Maurer et al., 2003), duration (Baldeweg et al., 1999) or tone pattern (Kujala, Myllyviita, Tervaniemi, Alho, Kallio & Näätänen, 2000) has so far been investigated in dyslexic populations. Consistently reduced MMN has been reported to phoneme changes for adults with dyslexia (Baldeweg et al., 1999; Schulte-Körne et al., 2001), children with dyslexia (Schulte-Körne et al., 1998) and also infants at risk of dyslexia (Maurer et al., 2003). These findings support the Phonological Representations Hypothesis of dyslexia, in positing a fundamental difficulty in the encoding and/or storage of phonological information. Findings with non-speech stimuli varied according to more isolated factors such as frequency and duration are less consistent, with no single parameter change yet shown across studies to be consistently affected in dyslexia. Thus whilst non-speech MMN deficits are undoubtedly present, we do not yet understand the auditory parameters determining their nature.

4.3.5 The N1 and dyslexia

Fewer studies have examined the N1 component in relation to dyslexia. Whilst the MMN indexes a level of auditory encoding that is thought to link directly to higher cognitive processes such as echoic memory, the N1 represents a more transient level of stimulus feature detection. As such, group differences of N1 would place the locus of auditory deficit at a more basic stage of auditory processing. Findings from studies involving adult versus child dyslexics differ. In two studies with adult dyslexics and using the magnetic equivalent of the N1, the 'N1m' Nagarajan, Mahncke, Salz, Tallal, Roberts and Merzenich (1999) as well as Helenius, Salmelin, Richardson, Leinonen and Lyytinen (2002) found increased N1m amplitudes to tones and speech stimuli respectively. Helenius et al. suggested that this enhancement may reflect activation of an abnormally large, non-specialised neuronal population, suggestive of neural reorganisation/compensation. Interestingly, Nagarajan et al. also found reduced N1m amplitudes to subsequent stimuli presented very soon after the first – this could suggest that the unusually large initial N1m response adversely effects subsequent processing through the longer neuronal recovery times needed. It should be noted, however, that this study had small sample sizes, with data from 4 dyslexic and 5 controls reported (the Helenius et al. study had equivalent group sizes of 10 and 9).

With regard to children, the only current N1 evidence concerns children with a primary diagnosis of language impairment and co-existing reading difficulties. In a study by Neville, Coffey, Holcomb and Tallal (1993) twenty two children with co-existing language and literacy difficulties demonstrated reduced N1s to tone stimuli over the right hemisphere at the shortest ISI rate (200ms as compared to 1000 and 2000). The paradigm in this study was an active deviant detection activity, with sounds also being presented from three different spatial locations. The presence of these additional performance demands therefore makes it harder to attribute the N1 differences to a specific auditory variable, as opposed to the possibility it is just indexing the inefficiency of a compromised auditory processing system under stress.

To summarise the N1 studies of dyslexia, the heterogeneity of methods is mirrored by varied results. As a whole the findings do point to the strong possibility of auditory processing differences between dyslexic and typically-developing readers even at this early stage of processing. Similarly to the MMN studies, what is not clear is the auditory parameters determining these differences and the role of developmental change.

4.3.6 The AMFR and dyslexia

Two further studies of note at this point are those carried out by Menell, McAnally & Stein (McAnally & Stein, 1997; Menell & McAnally, 1999). In the first of these studies (McAnally & Stein, 1997) the authors investigated adult dyslexic ERP responses to amplitude modulated 200ms tones, modulated at rates between 20 and 80Hz (n=15). McAnally et al. looked at an ERP component occurring before the N1 which they identified as the amplitude modulation following response (AMFR), likely within the latency range observed here to have a cortical generator. The authors found consistently reduced AMFR amplitudes within the dyslexic group as compared to their controls. In a second study (Menell and McAnally, 1999) these findings were extended to modulation rates between 10 and 160Hz (n=20) and strong associations were found with participants' behavioural amplitude modulation detection thresholds. Menell and McAnally (1999) also examined brainstem responses to click trains, finding no group differences at this level.

Although these studies looked at overall amplitude modulation sensitivity, as opposed to the focus upon AEO rise time in this thesis, the findings provide further evidence that basic cortical auditory processing may be different in many dyslexic individuals. These studies also suggest that auditory parameters associated with amplitude envelopes are influential. The authors note that the stimuli in these studies may have confounded amplitude modulation rate with responses to stimulus onset, thus this point needs clarification.

4.4. Key research questions of the current thesis

Having now reviewed the previous studies of relevance to this thesis, the three key research questions to be answered are summarised below. Chapters 5 to 8 describe the experiments carried out to seek such answers.

1) The Phonological Representations Hypothesis of dyslexia requires that the relationship between representation specificity and phonological processing be word–specific. Can evidence be found for word-specific associations between phonological representation quality and performance on input and output phonological processing tasks?

2) Underspecified phonological representations could arise because lexical factors act differently in developmental dyslexia. Can an in-depth exploration of phonological neighbourhood density effects inform our understanding of why dyslexic children's phonological representations are underspecified?

3) Underspecified phonological representations may arise from a more basic sensory deficit. Can a more basic auditory processing deficit, specifically, amplitude envelope onset sensitivity, explain the phonological representation deficit in dyslexia?

Chapter 5 - Testing the Phonological Representations Hypothesis of Dyslexia

5.1 Introduction

The aim of the experiments in this chapter was to test the Phonological Representations Hypothesis of dyslexia in a word-specific manner. As laid out in chapter 2, the Phonological Representations Hypothesis proposes that the phonological deficit in dyslexia can be attributed to a difficulty in establishing well-specified phonological representations. This subtle deficit results in behaviourally manifested processing difficulties whenever high demands are placed upon the 'underspecified' representations.

There are only three direct tests reported in the literature which examine whether less well-specified phonological representations for *particular lexical items* cause phonological processing difficulties in tasks based on those items (Constable et al., 1997; Swan & Goswami, 1997b; Dietrich & Brady, 2001). Although these studies intimate a consistent relationship between phonological representational quality and performance on a range of phonological tasks from lexical decision through to spelling, because of the differing aims and methods of each study, more systematic evidence was deemed necessary.

5.1.1 Experimental Design

The key aim here was to compare performance on a range of phonological processing tasks with confrontation naming accuracy, the index of phonological representational specificity. To do this, aspects of design from all three of the above studies were used.

The first step was to choose a picture naming set that would also form the basis for the phonological processing tasks. Due to the carefully controlled range of word length and frequency in the set used by Swan and Goswami (1997a), it was decided to use the same 40 item set here (further features of this set are described in the methods section below). The task was adapted for computer presentation and to obtain a measure of picture naming consistency the same set was presented twice in the first assessment phase, with an interval of approximately six weeks between each presentation. Naming speed as well as naming accuracy was recorded. However, concerns about the recording reliability of the voice key method used meant that these reaction time data are not considered further within this thesis.

The next step was to design phonological processing tasks based on the same set of 40 words. To allow comparability with Constable et al.'s study, one input phonological processing task and one output phonological processing task from their battery were used. As an input processing task, auditory visual lexical decision was chosen. In this task a picture is presented alongside a spoken word or a very closely-related non-word. The participant must decide whether the spoken label given correctly matches the picture with a yes/no judgement. This task requires a comparison between the phonological form presented and the participant's stored phonological representation for that item, and so requires a high degree of phonological representation specificity. As an output task, nonword repetition was chosen. Because the nonword types described by Constable et al. retained a considerable degree of phonological similarity with the lexical items they were derived from and we know from existing studies that stored lexical knowledge is important to success in immediate recall tasks (Schweikert, 1993), this activity again depends upon well-specified phonological representations.

Swan and Goswami (1997b) also compared picture naming accuracy with phonological *awareness* at different linguistic levels. However, because task procedure also varied with linguistic level it was an aim here to eliminate this confound. A picture match-to-sample task was designed that could be used across the phonological levels of syllable, onset-rime and phoneme. In this format a cue picture was presented first, followed by a target picture sharing the same phonological unit, alongside a phonologically related distracter. For each phonological unit size assessed, the basic cognitive demands of the task were thus the same.

The final key aspect of experimental design was the longitudinal aspect of the study. This enabled examination of how phonological representational specificity was developing over time across groups. As well as presenting children with the same picture naming set twice within a six week interval, the children were seen again two years later and administered the same picture naming task, alongside further related phonological tasks. The initial phase of assessment is henceforth referred to as 'Phase 1' (P1) and the two-year follow-up as 'Phase 2' (P2). The dyslexic children were paired with both chronological age matched controls and reading level matched controls.

5.1.2 Predictions

1. It was predicted that dyslexic naming performance would be significantly poorer than that of their age-matched peers. There is less consensus regarding dyslexic performance compared to reading-level matched peers, with one study reporting equal performance with this group (Snowling, von Wagtendonk & Stafford, 1988) and others reporting poorer performance (Wolf, 1991; Swan & Goswami, 1997; Nation et al., 2001). The a priori prediction here was that, following Swan and Goswami (1997a) using the same picture naming set, dyslexic naming performance would also fall below that of their reading level peers.

2. In line with the Phonological Representations Hypothesis (PRH), it was predicted that the dyslexic group would manifest more phonologically-based naming errors that the other groups. A greater effect of word length was also predicted for the dyslexics as naming longer words requires more phonological information to be specified and retrieved from long-term memory, as well as retained in short-term memory.

3. It was predicted that the underspecified phonological representations of the dyslexic group would result in greater naming inconsistency than the controls if presented with the same picture stimuli on different occasions.

4. Direct relationships were predicted between the dyslexics' representational quality, as indexed by picture naming, and performance on related phonological processing tasks.

5. In considering dyslexia as a developmental disorder a final prediction was that performance across both naming and phonological processing tasks would improve over time. It remained a question, however, as to whether the dyslexics would catch up with their chronological age-matched peers, maintain a consistent lag, or whether the performance gap would widen.

5.2 Phase 1 Methods

5.2.1 Participants

A group of twenty four dyslexic children were recruited to take part in all the experiments reported in chapters 5 to 8[3], alongside 25 chronological age-matched and 24 reading age-matched controls. Phase 1 assessments took place between January - July 2001 and Phase 2 assessments between January – July 2003.

Group characteristics at the beginning of Phase 1

i) Children with dyslexia

The dyslexic children were selected from schools within the London area where they were receiving specialist teaching for their literacy difficulties. Children were identified as dyslexic if they had average or above average intelligence, normal sensory ability, no documented neurological damage, no documented exposure to any social or educational deprivation, yet whose reading achievement was at least eighteen months below that expected by their age and intelligence. Reading ability was assessed using

[3] For practical reasons only a small subgroup of these children have taken part in the neurophysiological experiments of chapter 8.

the British Ability Scales (BAS; Elliott, Smith & McCulloch, 1996). Intelligence was measured with the Wechsler Intelligence Scale for Children (WISC-III; Wechsler, 1992). A cut-off score of 85 and above was used (85 being one standard deviation below the mean). A pro-rated short-form IQ was administered following Sattler (1982), consisting of 4 subtests: block design, picture arrangement, similarities and vocabulary. Additional standardised measures carried out were the Graded Nonword Reading Test (Snowling, Stothard & McLean, 1996) and the BAS Spelling and Mathematics subtests. There were 5 girls and 19 boys in the dyslexic group, in line with the consensus finding that dyslexic children are predominantly male (Snowling, 2000).

ii) Chronological age (CA) matched control group

Comparison of dyslexic children with their chronologically age-matched peers will not only show areas in which they are developmentally delayed but areas of function which are developmentally normal. The 25 CA children were individually matched as closely as possible to the dyslexic group for chronological age and IQ as measured by the WISC short-form. The groups were also matched for socio-economic background. This was indexed via the occupational skill level of the main income-bearer within each family, calculated using the 4-level skill index of the Standard Occupational Classification 2000 (SOC2000; Office for National Statistics, 2000).

The groups were not matched for gender. Because of previous findings demonstrating a gender difference favouring boys in picture naming tasks (Rudel, Denckla, Broman & Hirsch, 1980; Wolf & Gow, 1986) and because the presence of picture naming deficits in dyslexia was being extensively investigated in this thesis, it was felt that a large number of boys in the control groups would prove too stringent a test. Accordingly in the CA group there were 15 girls and 10 boys. Children were also excluded if:-

1) their first language was not English
2) they were known to have prolonged or frequent absences from school
3) they had noticeable or documented hearing or articulatory problems

iii) Reading level (RL) matched control group

The rationale for including a reading level comparison group is that if reading level is controlled, then resultant group differences in task performance cannot be attributed to differences in reading experience. It thus highlights developmental deficits that are more likely to be the cause than consequence of the dyslexics' reading difficulties. The group does introduce complications of its own however. Specifically, reading age and mental age become confounded and so equivalent scores of dyslexic and RL children do not rule out the possibility that the older dyslexic children are using a more sophisticated compensatory strategy to achieve similar levels of performance.

Using the same exclusionary criteria as for the CA group, the 24 RL children were reading at an age-appropriate level and were as closely individually matched as possible to the dyslexic group in reading age, as measured by the BAS, and IQ. The groups were also matched for socio-economic background using the SOC2000. The RL group contained 13 girls and 11 boys.

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All participants were volunteers whose parents gave informed written consent. The study was approved by the Joint UCL/UCLH Committees on the Ethics of Human Research. An overall summary of participant characteristics at the beginning of Phase 1 is shown in Table 5.1. Statistically significant performance differences between the children with dyslexia and each control group, as indicated by one way ANOVAs, are indicated by asterisks. All recruited children were also required to pass a hearing screen at 20dB.

Of note is the high reading age of the CA group in relation to their chronological age. This is due to the standardisation of the BAS (re-standardised in

1996, just before the advent of the National Literacy Strategy), which is known from other studies to produce elevated literacy ages (Richardson, Thomson, Scott & Goswami, in press).

Table 5.1 Participant characteristics at the initial assessment Phase (P1)

	Dyslexic	CA	RL
N	24	25	24
Age in years and months	9,0 (11m)	9,0 (8m)	7,11 (4m)
Reading Age in years and months	7;6 (6m)	10;2*** (17m)	7;11 (7m)
Reading Ability Score[a]	101.7 (11.7)	142.5*** (14.7)	108.3 (13.0)
Spelling Ability Score[a]	69.0 (12.1)	107.8*** (16.2)	85.5*** (12.1)
Maths Ability Score[a]	92.7 (20.3)	114.6*** (16.0)	94.4 (14.0)
Graded Nonword Reading/20	7.4 (5.5)	15.7*** (4.0)	11.3* (5.1)
IQ	109.1 (11.4)	111.9 (11.0)	105.7 (10.6)

Note. Standard deviations are shown in parentheses

[a] BAS 'Ability scores' reflect raw ability, with no adjustment for age
***p<.0001, **p<.01, *p<.05

A summary of the assessment schedule at Phase 1 is given in Table 5.2. The experimental measures address all three of the key research questions of this thesis (see p.70), addressed separately in chapters 5, 6, and 7. The tasks below are colour-coded to reflect these distinctions. In this chapter the measures highlighted in green are the focus.

Table 5.2 Summary of assessments at Phase 1

Session	Assessments
1.	WISC Block Design, BAS Reading, Picture naming Time 1, Object recognition task
2.	WISC Vocabulary, Graded Non-word Reading, BAS Spelling
3.	WISC Picture Arrangement, Non-word repetition, AEO detection, RAN
4.	WISC Similarities, Auditory-visual lexical decision, Rapid frequency discrimination, Oddity task
5.	Syllable and Rime tasks, Short-term memory task
6.	Temporal order judgement, Onset task
7.	Coda task, BAS Maths
8.	Picture naming Time 2

Note. AEO = Amplitude Envelope Onset

Key: Chapter 5, Chapter 6, Chapter 7

Sessions 1 and 2 were always carried out first. Sessions 3 and 4 were then administered in a counter-balanced order across children. The order of sessions 5, 6 and 7 was also counterbalanced. Session 8 was the final session, with approximately 6 weeks elapsing between the first and last assessment sessions for each child. Testing was undertaken in a 1:1 format, in a quiet room located in the child's school.

Group characteristics at the beginning of Phase 2

For the second phase of testing as many as possible of the same children were seen again. It was not possible to trace or visit all the original children and so three dyslexics, three RL controls and 6 CA controls are omitted from the Phase 2 data. The resultant group characteristics are shown in Table 5.3. Significant differences between groups are highlighted with asterisks.

Table 5.3 Participant characteristics at the beginning of Phase 2

	Dyslexic	CA	RL
N	21	19	21
Age in years and months	11;1 (12m)	10;11 (8m)	9;11 (4m)
Reading Age in years and months	9;8 (22m)	14;3 (22m)	11;2 (18m)
Reading Ability Score[a]	131.4 (23.7)	173.6*** (12.9)	151.3** (12.4)
Spelling Ability Score[a]	91.3 (11.6)	129.2*** (16.5)	110.1*** (12.7)
Maths Ability Score[a]	119.8 (17.6)	148.7*** (15.7)	125.4 (20.6)
Graded Nonword Reading/20	13.9 (3.8)	18.7*** (1.8)	18.1*** (1.9)
IQ	109.1 (11.6)	106.7 (10.7)	112.8 (11.1)

Note. Standard deviations are shown in parentheses

[a] BAS 'Ability scores' reflect raw ability, with no adjustment for age
***p<.0001, **p<.01, *p<.05

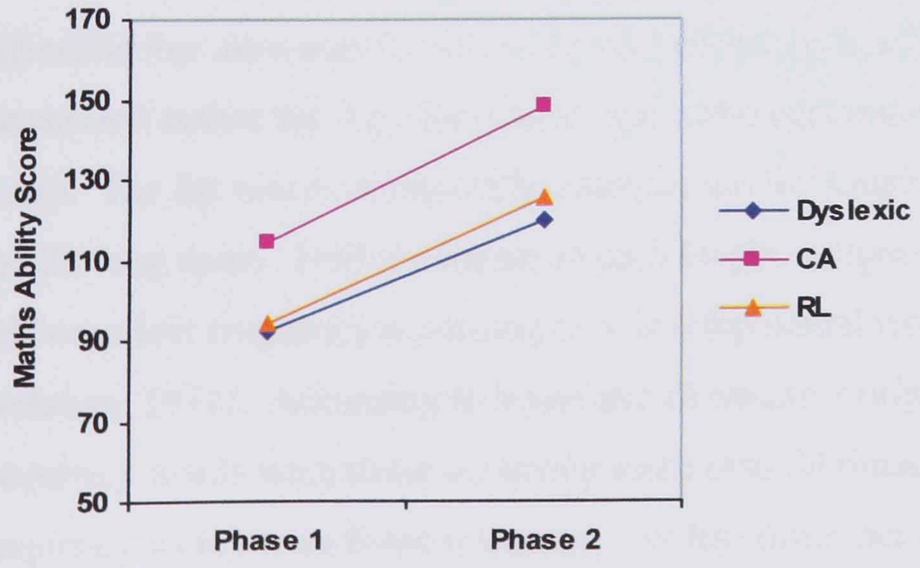
As can be seen, the dyslexic and RL groups were no longer matched for reading ability. A graph to show the relative reading progress of the three groups between phases 1 and 2 is shown in Figure 5.1. In order to assess the statistical significance of these different reading trajectories a one way ANOVA was carried out with reading progress in months as the dependent variable and reading group as the between-subjects factor. This analysis yielded a main effect of group, $F(2,58) = 9.41$, $p<.001$. The reading progress made by both the CA and RL groups was significantly greater than that of the dyslexic group (DYS vs. CA, $F(1,38) = 17.01$, $p<.001$; DYS vs. RL, $F(1,40)$

= 7.81, p<.01). There was no significant difference between the reading progress made by the CA and RL groups (F(1,38) = 1.98, p = 0.16).

Figure 5.1 Reading progress between assessment Phases 1 and 2

This pattern is contrasted with progress in mathematics between Phases 1 and 2, shown in Figure 5.2. A one way ANOVA taking progress in maths as the dependent variable and group as the between-subjects variable yielded no main effect of group, F (2,58) = 1.1, p = 0.3.

Figure 5.2 Mathematics progress between assessment Phases 1 and 2



A summary of the assessment schedule at Phase 2 is given in Table 5.4. For each child approximately 4 weeks elapsed between sessions 1 and 5. The order of sessions 2 and 3 was counterbalanced across children, otherwise sessions were administered in the order shown.

Table 5.4 Summary of assessments at Phase 2

Session	Assessments
1.	BAS Reading, Picture naming, RAN, Graded Non-word Reading
2.	BAS Spelling, AEO discrimination, Auditory-visual lexical decision
3.	Non-word repetition, AEO detection, Paired associate learning I
4.	Vowel substitution I. Paired associate learning II
5.	Vowel substitution II, Short-term memory task, BAS Maths

Note. AEO = Amplitude Envelope Onset

Key: Chapter 5, Chapter 6, Chapter 7

5.2.2 Experimental tasks and procedure

Picture naming

The 40 item picture naming set (Swan & Goswami, 1997a) consisted of black and white line drawings for 40 picturable objects, assessed through informal piloting by the present author for their familiarity and name agreement with the youngest target age group. The list was systematically manipulated for length and frequency, with 20 short and 20 long items. Half the names in each length category were high frequency and half were low frequency according to a developmental word count (Carroll, Davies & Richman, 1971). According to Swan and Goswami's original selection criteria high frequency words were those occurring more than 20 times per million and low frequency words were those occurring 5 or less times per million. The pictures were presented by computer. Items appeared on the screen in a random order and children were asked to respond with the name as quickly and accurately as possible. Within Phase 1 the task was given once in the initial test session ('Time 1') and then again in the final test session ('Time 2') to assess consistency of naming performance.

Table 5.5 Stimulus list - picture naming tasks

Short Length		Long Length	
High Frequency		High Frequency	
dust	(59)	exercise	(77)
clock	(55)	television	(72)
flag	(42)	electricity	(59)
frame	(41)	potatoes	(44)
pipe	(39)	factory	(40)
queen	(36)	triangle	(34)
chain	(35)	audience	(34)
globe	(34)	alphabet	(29)
tent	(31)	hospital	(25)
belt	(29)	telescope	(22)
Low frequency		Low frequency	
vest	(3)	propeller	(5)
quill	(3)	protractor	(4)
claw	(3)	binoculars	(2)
maze	(2)	harmonica	(2)
yawn	(2)	boomerang	(2)
moat	(2)	tentacles	(1)
harp	(1)	banister	(1)
whisk	(1)	dominoes	(*)
wick	(1)	escalator	(*)
clog	(*)	acrobat	(*)

Note. Frequency counts per million from Carroll, Davies & Richman, 1971.

Following Stimley and Noll (1991), names with a frequency of occurrence of less than one per million (denoted as *) were designated as "1 per million" so that mean frequencies of occurrence could be calculated.

Object recognition task

An object name recognition test was administered after the initial picture naming, to ensure that the picture names were known lexical items for each child. The forty target pictures from the picture naming task were each matched to 4 distracter pictures; a visual foil that physically resembled the target, a semantic distracter that had a similar meaning to the target, a phonological foil that sounded similar to the target name and a control foil that was unrelated to the target. The five pictures were presented in a pentagonal arrangement on the computer screen. The position of the target and distracters was randomised in order to discourage a positional response bias. Children were verbally presented with the target item and asked to point to the matching picture. Items unfamiliar to children were then discounted from any further analysis for that individual. A full list of target names and their distracter items are given in Appendix 1.

Input and output phonological processing tasks

In order to create parallel input and output phonological processing tasks the twenty long words from the forty item set were used to form closely related nonwords. The strategy used was the same as that applied by Constable, Stackhouse and Wells (1997). Two set of nonwords (A and B) were designed. Nonword Type A was formed by modifying the onset consonant of the third or final syllable to imitate a perseverative-type speech error (e.g. escalator - [eskəleɪkə]). Nonword Type B was formed by transposing two onset consonants (e.g. escalator - [estəleɪkə]). Digitised recordings of both types were then included in auditory visual lexical decision (input processing) and nonword repetition (output processing) tasks.

Auditory visual lexical decision

Polysyllabic items from the picture naming set were presented visually on the computer screen in a pseudo-random order, with simultaneous auditory presentation through headphones of the target word or one of the two matched nonwords. Children were instructed to say, "yes" if they thought the spoken realisation was the correct picture name or, "no" if they thought it was incorrect.

Nonword repetition

Both types of nonword stimuli (20 type A + 20 type B = total of 40 items) were presented in a pseudo-random order through headphones and children were instructed to repeat each item as quickly and accurately as possible following a response signal. Responses were transcribed online as well as being audio-recorded on minidiscs for subsequent transcription and analysis.

Phonological awareness measures

In order to further explore the relationship between representational quality and phonological awareness, picture-based tasks at the three linguistic levels of syllable, onset-rime and phoneme were also administered. In this design children saw a cue picture and had to choose from a further two pictures the one that shared the specified phonological unit with the cue. The task levels can be seen in Table 5.6 below and the stimulus items in Appendix 2. In order to build on the findings generated by the 40 item picture naming task, it was intended to use these items as stimuli within the phonological awareness measures as often as possible. This proved hard to achieve in practice for the 20 polysyllabic words - due to the difficulty in finding suitably matched cues, targets and distracters only 11 could be incorporated, and this was within the syllable level task only. However, for the 20 monosyllables, 19 were incorporated as a cue item twice – once at the onset (single consonant) or rime level and once at 'smaller unit' phoneme level (onset - consonant cluster, or coda – single consonant/consonant cluster). For the one item, 'yawn' that was not featured twice at these levels (only once in final consonant singleton task), it did appear as a cue in the syllable task, thus ensuring that exposure to all the 20 monosyllables was equal.

Table 5.6 Overview of items for picture set used at each phonological level

Task	Trials[a]
Syllable	6 x SL x HF; 6 x SL x LF; 6 x LL x HF; 6 x LL x LF
Rime	7 x HF; 7 x LF
Onset (single consonant)	7 x HF; 7 x LF
Onset (consonant cluster)	7 x HF; 7 x LF
Coda (single consonant)	7 x HF; 7 x LF
Coda (consonant cluster)	7 x HF; 7 x LF

[a]The four stimulus classes are Short Length x High Frequency (SL x HF), Long length x High Frequency (LL x HF), Short Length x Low Frequency (SL x LF), and Long Length x Low Frequency (LL x LF). Only syllable level featured polysyllabic items. All other levels contained monosyllables only.

The six tasks were introduced to children separately, however the basic format remained constant. For each trial, a cue picture was presented at the top of the computer screen with two further pictures displayed below. One of the bottom pictures shared a phonological unit with the cue (the target), whilst the other was a closely related phonological distracter. Because of the specific interest here on performance in the light of phonological representation quality and because the pictures featured in these tasks had now expanded beyond the original forty item set, in each experimental trial the children were first asked to name all three pictures. The aim was to assess whether each participant had unprompted access to the correct phonological representation of the stimulus items prior to the phonological analysis component of the task. If children named the pictures incorrectly or gave a null response, the correct name was provided by the experimenter and the child repeated it. The trial then proceeded with the child pressing a button associated with the picture they believed to share the common unit. The computer recorded the accuracy of the child's response for each trial. The only concession to task inequity was at the syllable level. At this level children were asked to match the cue picture to a target which shared the same *number* of syllables, as opposed to an identical syllabic unit. Although this procedural difference made the task harder in terms of short-term memory load, this design decision had to be taken due to the very small number of picturable polysyllabic words sharing identical syllable units, as well as theoretical difficulty in defining syllable boundaries. At the syllable level there were two word length conditions. Items in the short length condition contained 1-2 syllables and items in the long length condition contained 3-4 syllables.

5.3 Phase 1 Results

5.3.1 Picture naming

Accuracy of naming

The number of items correctly named for each child was noted and following Katz (1986), any incorrectly named object that was not familiar to the child was eliminated from consideration for that individual and the mean percentage scores computed[4]. These are presented in Table 5.7 for Time 1 and Table 5.8 for Time 2 respectively.

Table 5.7 Adjusted % correct in the picture naming task, Time 1

	Dyslexic	CA	RL
SL x HF	95.83 (6.54)	98.80 (3.32)	91.25 (7.97)
LL x HF	85.42 (13.18)	89.60 (7.90)	91.67 (9.63)
SL x LF	55.83 (14.42)	64.00 (12.91)	47.08 (17.06)
LL x LF	50.00 (24.85)	69.90 (12.07)	50.83 (19.32)

Note. Standard deviations are in parentheses

[4] Familiarity was ascertained by online familiarity questioning for items a child was unable to name and later confirmed by administration of the object recognition task for unnamed items.

Table 5.8 Adjusted % correct in the picture naming task, Time 2

	Dyslexic	CA	RL
SL x HF	96.25 (8.24)	99.20 (2.77)	91.74 (7.78)
LL x HF	87.50 (12.25)	93.60 (7.00)	94.35 (7.88)
SL x LF	63.75 (19.29)	69.60 (12.07)	51.74 (17.75)
LL x LF	57.50 (24.18)	72.80 (13.54)	60.87 (18.07)

Note. Standard deviations are in parentheses

The four stimulus classes are Short Length x High Frequency (SL x HF), Long length x High Frequency (LL x HF), Short Length x Low Frequency (SL x LF), and Long Length x Low Frequency (LL x LF).

In order to determine how best to analyse the Time 1 and Time 2 data a paired sample T-test was first carried out to confirm whether or not children's scores were significantly different between the two time points. This found that the scores were significantly different, $t(60) = -10.92$, $p<.001$, with higher scores occurring at Time 2. In light of this the data were not combined and Time 1 results are focused on in the accuracy analysis below. Even at Time 1 ceiling scores are observable for CA children in the SL x HF condition. Ceiling scores are also observed within other results of this chapter. Due to concerns about the effects of these on the planned analyses, two separate ANOVAs were conducted in each instance; the first used the untransformed data and the second used a log transformation of the same data. Because the pattern of significances remained identical or nearly identical in all cases, the analyses reported in this chapter consistently use untransformed data.

A 3 (reading group) x 2 (stimulus length) x 2 (stimulus frequency) ANOVA with reading group as the between-subjects factor and repeated measures on length and frequency was used to look at group differences and the performance effects of contrasting stimulus classes at Time 1. The percentage of total correct picture naming responses was taken as the dependent variable. This analysis yielded a main effect of reading group, $F(2,70) = 8.64$, $p<.001$. Post-hoc tests indicated that the CA controls correctly named significantly more pictures than the dyslexics, $F(1,47) = 11.84$, $p<.001$ and the RL controls, $F(1,47) = 18.4$, $p<.001$. There was no significant difference in the picture naming scores obtained by the dyslexic and the RL control groups ($F(1,46) = 0.29$, $p = 0.6$). The analysis also yielded main effects of length, $F(1,70) = 4.24$, $p<0.05$ and frequency, $F(1,70) = 496.69$, $p<0.001$. Participants were significantly better at naming pictures with short names than with long names (75.55% vs. 73.01% across groups) and at naming pictures with high frequency than with low frequency names (92.19% vs. 56.37% across groups). Interestingly, the analysis also showed a significant two-way interaction between reading group and length, $F(2,70) = 5.52$, $p<0.01$. Post-hoc testing revealed that the dyslexics were the only group to show the length effect: they were significantly better at naming pictures with short names than long names, $F(1,23) = 8.99$, $p<0.01$.

There was also an interaction between length and frequency, $F(1,70) = 4.86$, $p<.05$. Post-hoc investigation found that this interaction was caused by long length exerting an adverse effect on high frequency items only (effect of length on high frequency words, $F(1,70) = 29.49$, $p<.0001$; effect of length on low frequency words, $F(1,70) = 0.38$, $p = 0.5$).

Error analysis – Time 1

An analysis of children's erroneous picture naming responses at Time 1 was undertaken to examine whether these errors were predominantly semantic or phonological in nature and whether this pattern would differ with reading group. An error coding system was developed from adult studies of picture naming in aphasia (e.g. Kohn & Goodglass, 1985), using only those coding categories applicable to the children's errors and found to have good inter-rater reliability[5]. For each subject, the

[5] Inter-rater reliability was ascertained from an initial scoring of 10 children's naming performance (randomly selected), carried out by the author and another qualified Speech and Language Therapist.

number of errors in each category was calculated as a percentage of the total number of errors made across all categories. The mean percentage distribution for each group is shown in Table 5.9.

Table 5.9 % Distribution of coded errors on the picture naming task, Time 1

Error Category	Dyslexic	CA	RL
1. Perceptual	0.00	0.50	0.35
2. Semantic	47.04	62.31	52.13
3. Phonological (word)	0.74	0.00	1.06
4. Phonological (nonword)	5.19	0.50	1.06
5. Semantic/Phonological	8.15	7.54	5.67
6. Circumlocution	20.00	16.58	17.73
7. Partial realisation of name	0.00	0.00	0.35
8. No response	18.89	12.06	23.05

As can be seen, the dyslexics had noticeably more phonological nonword errors than the other two groups, as well as an increased number of semantic-phonological errors and circumlocutions. These differences did not reach statistical significance, possibly due to the small sizes of N.

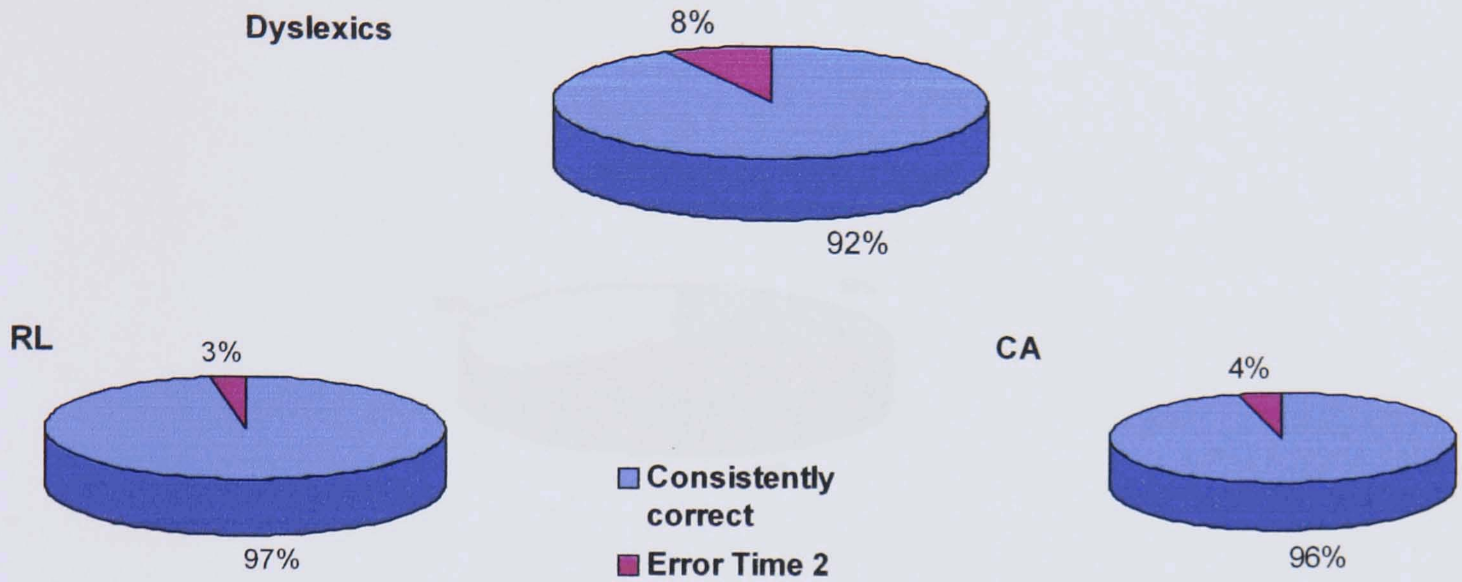
Naming consistency

The picture naming task was administered twice with the goal of examining the stability of performance for each group. Consistency of responding was assessed in two ways. Firstly, items that were correctly named at Time 1 were examined at Time 2 to see whether they remained accurate. Percentage scores, representing the number of words that were correct on Time 1 and also on Time 2 (i.e. the number of consistently correct responses), as well as those correct at Time 1 but then incorrect at Time 2 were

Classifications that yielded a Kappa coefficients of less than 0.6 (Fleiss, 1981) at this stage were deemed unsuitable to further use and included 'perceptual/semantic' and 'perceptual/phonological'.

computed for each individual by dividing the number of these occurrences by the total number of correct responses at Time 1 (see Figure 5.3)[6].

Figure 5.3 Items correctly named at Time 1 – outcomes at Time 2



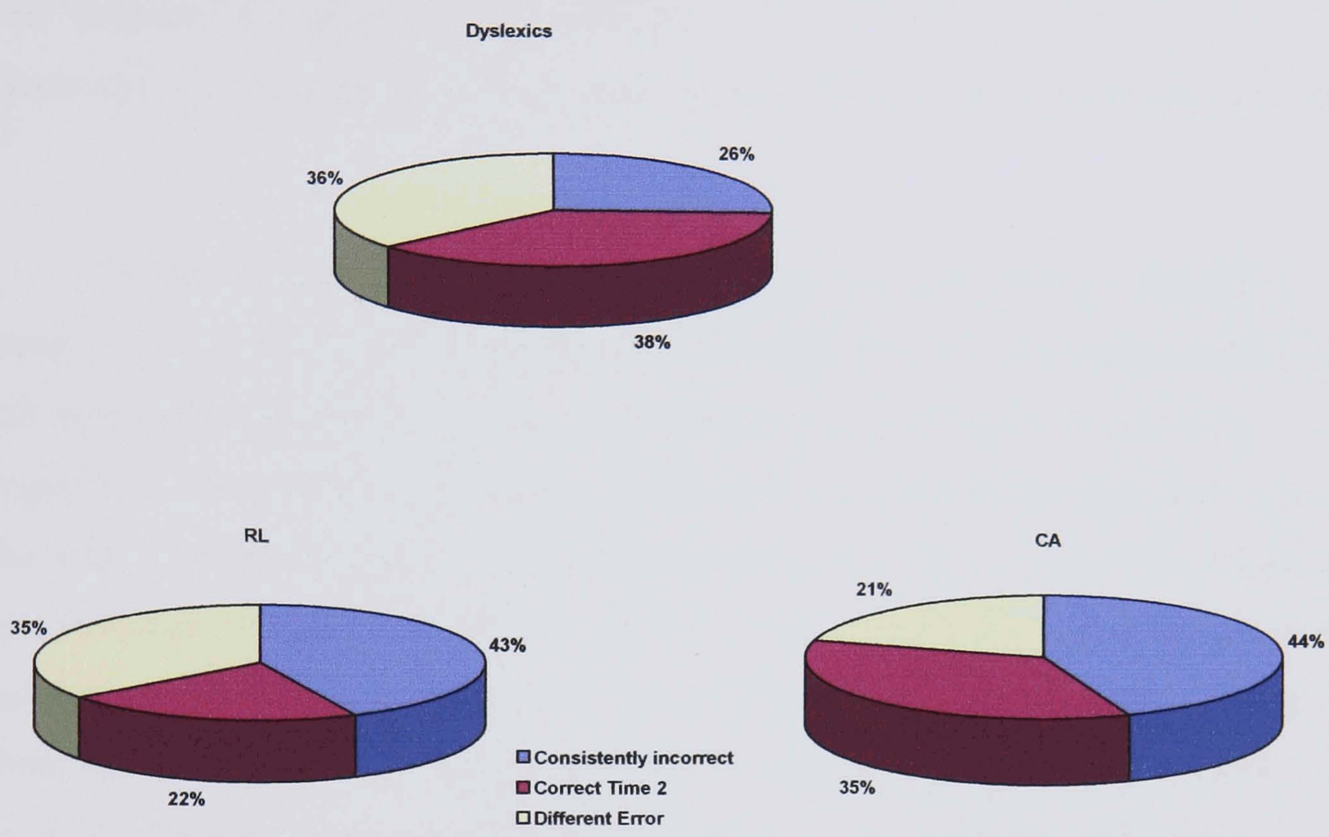
The results of a one way ANOVA revealed significant group differences in consistency $F(2,69) = 6.13$, $p<.01$, with follow up analyses revealing that the dyslexic group had a significantly smaller proportion of consistently correct responses than either the CA match group or the RL controls (DYS vs. CA, $F(1,47) = 5.87$, $p<.05$; DYS vs. RL, $F(1,47) = 7.94$, $p<.01$).

The second analysis focused upon items incorrectly named at Time 1. At Time 2 these items could be correct or still in error. Errors could be the same or different to those at Time 1. For this analysis 'different' errors were either differences that changed the error category e.g. a phonological error changing to a semantic error, or a difference that did not change the error category e.g. a different semantic substitution made on both occasions. Figure 5.4 displays the group results for this analysis. The dyslexic

[6] It is noted that consistency could also be measured by looking at items named incorrectly at Time 1 and then correctly at Time 2. However, whilst the subsequent inability to name an item previously named is uncontrovertibly a sign of inconsistency, the ability to name a previously un-named item may also reflect learning processes. Although the latter phenomenon is interesting, investigation of inconsistency was the primary focus here and so confounding factors were avoided where possible.

group had the smallest proportion of consistent errors (DYS vs. CA, $F(1,45) = 17.59, p<.001$; DYS vs. RL, $F(1,47) = 11.76, p<.001$). The dyslexics thus had the most inconsistent naming pattern for both correct and incorrect realisations.

Figure 5.4 Items incorrectly named at Time 1 – outcomes at Time 2



5.3.2 Nonword repetition

The nonword repetition task was scored in terms of the number of nonwords correctly repeated (out of a total of forty). Group results converted to mean percentage correct scores are shown in Table 5.10. The analyses were based on transcriptions made by a single transcriber (JT) from the audio discs of the experimental sessions. In cases where this was not possible, the original transcriptions were used.

Table 5.10 % Nonwords correct in the nonword repetition task [a]

	Dyslexic	CA	RL
HF	80.63 (13.05)	91.00 (8.00)	85.63 (10.87)
LF	66.88 (16.07)	83.60 (13.84)	74.79 (12.81)

Note. Standard deviations are in parentheses

[a] Nonwords derived from High Frequency items = HF and from Low Frequency items = LF.

In order to look at group differences the data was entered into a 3 (reading group) x 2 (frequency) ANOVA with reading group as the between-subjects factor and with repeated measures on stimulus class frequency (high frequency versus low frequency). Mean percentage of nonwords correct was taken as the dependent variable. The analysis yielded a main effect of reading group, $F(2,70) = 5.73$, $p<.01$. Post-hoc tests indicated that the CA controls correctly repeated significantly more nonwords than the dyslexics, $F(1,47) = 11.36$, $p<.001$, but not the RLs, $F(1,47) = 3.80$, $p = 0.054$. There was no significant difference between the dyslexic and RL group, $F(1,46) = 2.33$, $p = 0.13$. There was also a main effect of frequency with all groups repeating nonwords derived from high frequency items more accurately than those from low frequency items, $F(1,70) = 25.31$, $p<.001$. There was no interaction between frequency and group, $F(2,70) = 0.27$, $p = 0.77$.

5.3.3 Auditory visual lexical decision

Accuracy scores are reported in Table 5.11. Accuracy is defined here as the correct detection of a lexical item as well as the rejection of both of the nonword derivatives. Raw scores were thus out of 20, and converted to mean percentages correct.

Table 5.11 % Correct in the auditory visual lexical decision task[a]

	Dyslexic	CA	RL
HF	97.08 (5.50)	100 (0.0)	97.92 (5.09)
LF	74.17 (12.83)	99.60 (2.00)	80.00 (16.68)

Note Standard deviations are in parentheses

[a] High Frequency (HF), Low Frequency (LF)

In order to look at group differences the data was entered into a 3 (reading group) x 2 (frequency) ANOVA with reading group as the between-subjects factor and with repeated measures on stimulus frequency. Mean percentage correct was taken as the dependent variable. The analysis yielded a main effect of reading group, $F(2,70) = 29.69$, $p<.001$. Post-hoc tests indicated that the CA controls made significantly more correct lexical decisions than the dyslexics and the RL controls (CA vs. DYS, $F(1,47) = 89.67$, $p<.001$; CA vs. RL, $F(1,47) = 35.18$, $p<.001$). There was no significant difference between the dyslexic and RL groups, $F(1,46) = 1.94$, $p = 0.2$. There was also a main effect of frequency with performance higher for trials associated with the high frequency versus the low frequency items ($F(1,70) = 47.34$, $p<.001$). An interaction between frequency and group was found, $F(2, 70) = 23.20$, $p<.001$. Post-hoc inspection of the data showed that this was due to ceiling effects for all groups in the high frequency item scores, resulting in no significant differences between groups. For the low frequency items the CA group were still at ceiling and thus performing significantly better than the dyslexics and RL controls, whose performance was adversely affected by the lower familiarity of items.

5.3.4 Associations between picture naming and input/output tasks

To investigate on a word-by-word basis the relationship between picture naming accuracy and performance on the auditory-visual lexical decision and nonword repetition tasks, conditional accuracy scores were calculated using both a by-item and a by-child analysis.

By item

Picture naming performance at Time 1 was taken as a reference point. Across groups, item performance on the Auditory Visual Lexical Decision (AVLD) and Nonword Repetition (NWR) tasks was assessed and the mean proportion of correct responses was calculated separately for instances where the item had also been named correctly versus instances when the item had not been correctly named.

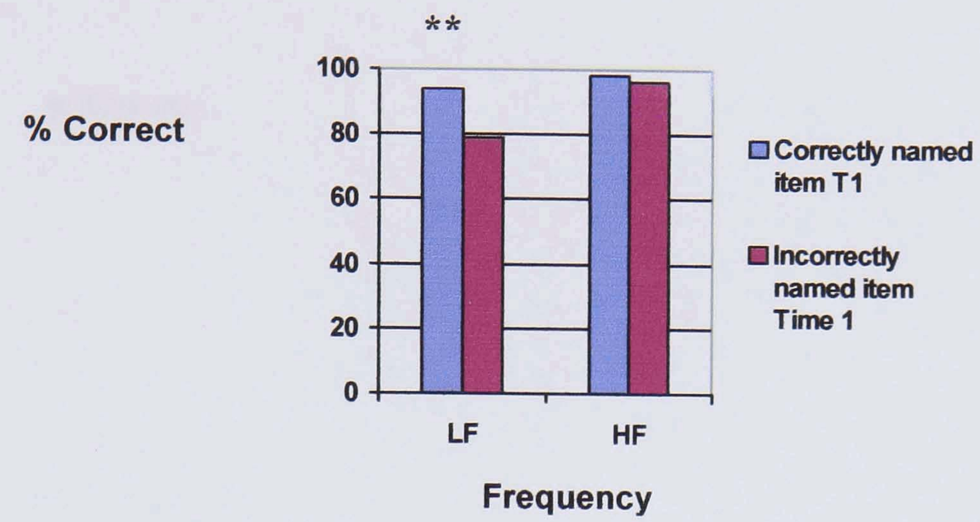
The correctness criteria used were complete accuracy on judgement of all word/nonword derivatives for an item in the AVLD task and 100% accuracy for repetition of both nonword derivatives in the NWR.

The contingent accuracy scores are shown in Figure 5.5. Asterisks signal a significant difference in accuracy between correctly and incorrectly named items. Due to the overall performance differences between low and high frequency items, these sets have been analysed separately.

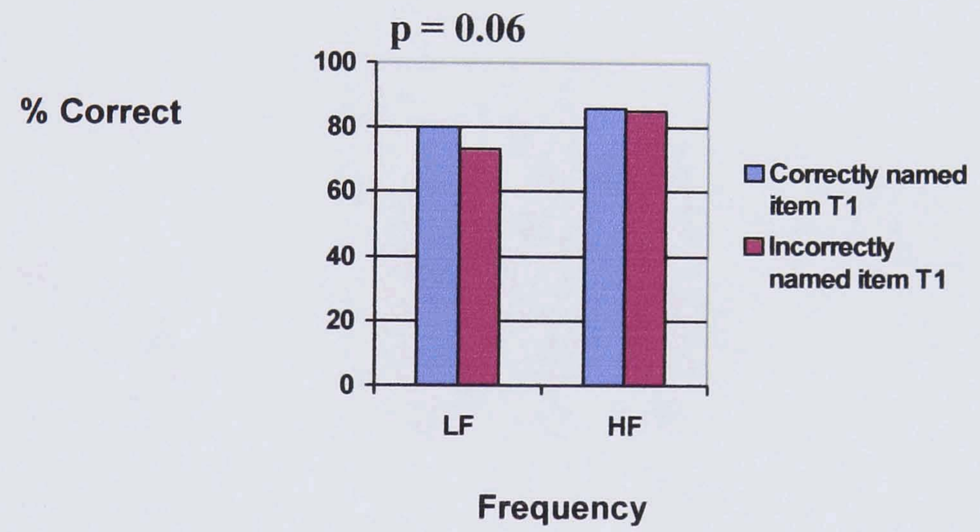
There was a significant performance difference between correctly versus incorrectly named items in the AVLD task for low frequency items, $F(1,58) = 8.34$, $p<.001$. A similar trend was seen for low frequency items in the NWR task, $F(1,58) = 3.50$, $p < 0.06$.

Figure 5.5 Accuracy on a) AVLD task and b) NWR task, contingent upon accurate picture naming at Time 1 (T1). Analysis by item. * p<.05, **p<.01,***p<.001.

a) AVLD



b) NWR



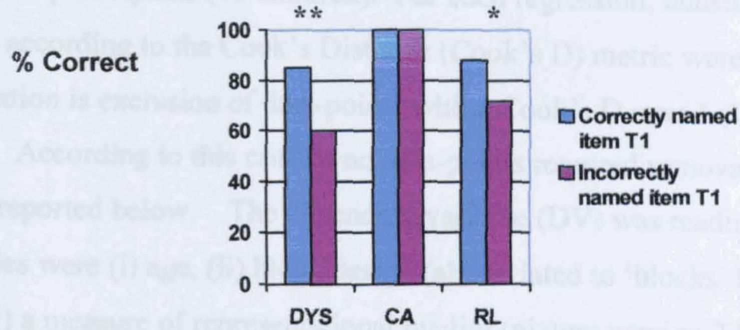
By child

A similar analysis was carried out by child. Accuracy in the AVLD and NWR tasks was separated according to whether a child had also been able to name the item correctly, versus occasions when the item had not been named correctly.

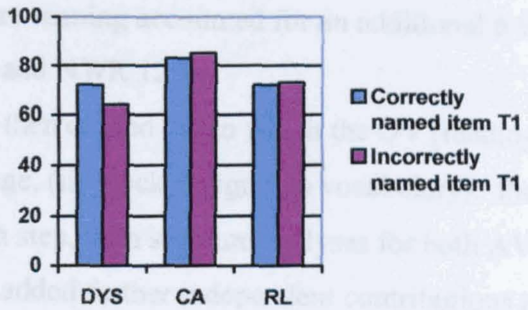
The contingent accuracy scores are shown in Figure 5.6. For clarity only low frequency items are displayed, due to greater variability and thus sensitivity exhibited by this stimulus class compared to the high frequency items.

Figure 5.6 Accuracy on a) AVLD task and b) NWR task, contingent upon accurate picture naming at Time 1 (T1). Analysis by child. * p<.05, **p<.01,***p<.001.

a) AVLD: Low frequency



b) NWR: Low frequency



Performance differences for correct versus incorrectly named items were significant in the AVLD task for the dyslexic ($F(1,46) = 8.23$, $p<.01$) and RL groups ($F(1,46) = 5.01$, $p<.05$). The CA results lacked sensitivity due to ceiling effects.

5.3.5 Picture naming and input/output phonological processing tasks as predictors of reading

The Phonological Representations Hypothesis asserts that poorly specified phonological representations are causally linked to the literacy difficulties of dyslexic children. A further analysis was therefore taken to look at the ability of the above measures, all essentially indices of phonological representation specificity, to predict reading skill.

A series of three 4-step fixed-entry multiple regression equations was computed across all participants (73 children). For each regression, unusual or influential data-points according to the Cook's Distance (Cook's D) metric were examined. The agreed convention is exclusion of data-points with a Cook's D over 1 (Tabachnik & Fidell, 2001). According to this criteria no data-points required removal for the regression series reported below. The dependent variable (DV) was reading and the independent variables were (i) age, (ii) block design (abbreviated to 'blocks' below), (iii) vocabulary and (iv) a measure of representational quality (picture naming T1, AVLD or NWR). Bivariate correlations between these measures are shown in Table 5.12. The regression analyses are summarised in Table 5.13 (further details given in Appendix 3) and show that all three measures contributed independently to the variance in reading performance – the picture naming accounted for an additional 6.9% of the variance in reading, AVLD 24.3 % and NWR 12 %.

An analysis was then carried out in which the DV (reading) and first three steps remained the same ((i) age, (ii) block design (iii) vocabulary). Picture naming was then retained as a fixed fourth step, with separate analyses for both AVLD and NWR as a fifth step. If these tasks added further independent contributions to the variance in reading this might suggest that as well as core phonological representation quality influencing reading skill, specific input/output processing skills reliant upon these representations add their own unique contributions to the end-point manifestation of reading difficulty. This was indeed found to be the case, with AVLD contributing a further 17% to the variance in reading performance and NWR an additional 8% (see Table 5.14).

Table 5.12 Bivariate correlations between standardised, phonological and literacy measures

Variable	Age	Blocks	Vocab.	Naming	AVLD	NWR	Reading
Age	---	-.16	.14	.18	.24**	-.09	.31**
Blocks		---	.29*	.21	.18	.11	.19
Vocab.			---	.55***	.37**	.31**	.45***
Naming				---	.64***	.34**	.49***
AVLD					---	.44***	.66***
NWR						---	.45***
Reading							---

*p<0.05, *p<0.01, ***p<0.001

Table 5.13 Percentage of variance in reading explained by the different independent variables in separate four-step fixed-entry multiple regression equations.

	Dependent variable: Reading, R^2
Step 1: age	0.10**
Step 2: blocks	0.05**
Step 3: vocabulary	0.11***
Step 4: picture naming	0.07**
Step 4: AVLD	0.24***
Step 4: NWR	0.12***

*p<0.05, **p<0.01, ***p<0.001

Table 5.14 Percentage of variance in reading explained by the different independent variables in separate five-step fixed-entry multiple regression equations.

	Dependent variable: Reading, R^2
Step 1: age	0.10^{**}
Step 2: blocks	0.05^{**}
Step 3: vocabulary	0.11^{***}
Step 4: picture naming	0.07^{**}
Step 5: AVLD	0.17^{***}
Step 5: NWR	0.08^{***}

*p<0.01, **p<0.05, ***p<0.001

5.3.6 Phonological awareness measures

Phonological awareness performance is presented in Table 5.15 These scores are based on all the trials of each task, irrespective of whether the corresponding pictures of stimuli were correctly named or not. Performance in terms of scores adjusted for correct picture naming of the stimuli are shown in Table 5.16 Adjusted accuracy scores considered only those trials in which subjects were able to correctly picture name all three trial-related pictures. For ease of comparison, both unadjusted and adjusted scores are presented as mean percentages.

Table 5.15 % Correct for the phonological awareness measures - unadjusted

Task	Dyslexic	CA	RL
Syllable			
SL x HF	70.14 (25.78)	91.33 (21.47)	94.44 (14.30)
SL x LF	65.97 (29.38)	92.67 (15.43)	92.36 (14.80)
LL x HF	71.53 (24.03)	93.33 (15.02)	83.33 (21.87)
LL x LF	64.58 (26.20)	83.33 (23.90)	59.72 (27.36)
Rime			
HF	94.64 (11.27)	98.86 (4.30)	98.21 (5.34)
LF	91.07 (13.00)	96.57 (9.09)	92.86 (11.70)
Onset (single cons.)			
HF	90.48 (19.18)	98.86 (4.64)	97.62 (9.82)
LF	87.50 (15.62)	97.71 (11.83)	96.43 (10.20)
Onset (cons. cluster)	89.29 (12.23)	97.14 (9.09)	92.86 (13.46)
HF	85.71 (19.30)	95.43 (12.03)	87.50 (15.83)
LF			
Coda (single cons.)			
HF	86.90 (18.83)	98.86 (4.83)	92.26 (14.34)
LF	73.21 (23.98)	93.71 (13.93)	79.17 (21.23)
Coda (cons. cluster)			
HF	78.57 (24.73)	94.29 (11.20)	89.29 (13.10)
LF	75.00 (27.32)	94.86 (8.18)	79.76 (19.28)

Note. Standard deviations are shown in parentheses

The stimulus classes are Short Length x High Frequency (SL x HF), Long length x High Frequency (LL x HF), Short Length x Low Frequency (SL x LF), and Long Length x Low Frequency (LL x LF).

Table 5.16 % Correct for the phonological awareness measures - adjusted

Task	Dyslexic		CA		RL	
Syllable						
SL x HF	73.33	(24.23)	92.00	(21.89)	95.42	(13.87)
SL x LF	70.07	(30.34)	94.0	(15.03)	93.96	(10.38)
LL x HF	72.85	(24.23)	93.87	(14.11)	83.06	(20.40)
LL x LF	65.52	(37.05)	89.78	(26.00)	64.47	(38.44)
Rime						
HF	95.60	(11.20)	98.86	(4.04)	98.51	(5.67)
LF	98.26	(6.02)	96.88	(11.03)	96.88	(11.98)
Onset (single cons.)						
HF	94.39	(16.62)	98.86	(4.20)	97.62	(9.62)
LF	89.29	(14.12)	97.71	(11.82)	97.96	(9.02)
Onset (cons.						
cluster)	90.91	(10.12)	97.14	(9.72)	98.50	(7.26)
HF	87.38	(24.43)	95.65	(17.02)	93.64	(14.36)
LF						
Coda (single cons.)						
HF	87.01	(19.20)	99.43	(3.00)	92.55	(14.00)
LF	74.75	(22.87)	93.91	(15.00)	80.68	(26.00)
Coda (cons. cluster)						
HF	83.53	(18.98)	96.25	(7.45)	92.16	(13.73)
LF	78.94	(30.57)	98.70	(4.37)	85.19	(22.82)

Note Standard deviations are shown in parentheses

The stimulus classes are Short Length x High Frequency (SL x HF), Long length x High Frequency (LL x HF), Short Length x Low Frequency (SL x LF), and Long Length x Low Frequency (LL x LF).

For each of the six phonological awareness tasks and for unadjusted and adjusted scores, separate ANOVAs were carried out, with reading group as the between-subjects factor and repeated measures on frequency (and length for the syllable level). The percentage of total correct scores was taken as the dependent variable. A summary of the findings from both the unadjusted and adjusted score analyses by phonological awareness task is presented in Table 5.17. Where performance effects for a task vary upon adjustment for underlying phonological representation integrity this is signalled by a tick in the final column.

Table 5.17 Overview of unadjusted and adjusted scores for all phonological awareness tasks (significant differences featured, p<.05)

Task		Unadjusted Scores	Adjusted Scores	Change?
Syllable				
	(short length)			
	Group	CA = RA > DYS	CA = RA > DYS	✗
	Frequency	High freq = low freq	High freq = low freq	✗
	(long length)			
	Group	CA > RA = DYS	CA > RA = DYS	✗
	Frequency	High freq > low freq	High freq = low freq	✓
Rime				
	Group	CA = RA = DYS	CA = RA = DYS	✗
	Frequency	High freq > low freq	High freq = low freq	✓
Onset (single consonant)				
	Group	CA = RA > DYS	CA = RA, CA > DYS	✓
	Frequency	High freq = low freq	High freq > low freq	✓
Onset (consonant cluster)				
	Group	CA > DYS, RA = DYS	CA = RA > DYS	✓
	Frequency	High freq > low freq	High freq = low freq	✓
Coda (single consonant)				
	Group	CA > RA = DYS	CA > RA = DYS	✗
	Frequency	High freq > low freq	High freq > low freq	✗
Coda (consonant cluster)				
	Group	CA > RA = DYS	CA = RA > DYS	✓
	Frequency	High freq = low freq	High freq = low freq	✗

The Phonological Representations Hypothesis predicts that dyslexic individuals' performance on phonological awareness tasks will be specifically impaired for items with poor quality phonological representations, whilst for fully specified items the difficulty will reduce and perhaps even disappear. In terms of the data presented here, this would translate into differences between the dyslexic and CA groups for the unadjusted scores, with a reduction and perhaps eradication of these differences within the adjusted scores.

Looking at the unadjusted scores, the results show that the performance of the dyslexic individuals was consistently below that of their CA peers with the exception of the rime task. The dyslexics were performing with an accuracy equivalent to their RL peers for most tasks, with the exception of syllable (short length) and onset (single consonant) levels for which the dyslexics showed poorer performance. The scores adjusted for picture naming accuracy show a more mixed pattern. The difference between the dyslexic and RL group became non-significant for the onset (single consonant) task. For the onset and coda consonant cluster tasks group differences a group difference emerged between the dyslexic and RL group, the latter showing greater performance increases upon adjustment relative to the dyslexics. The pattern of differences between all groups remained the same in the syllable, rime and coda (single consonant) tasks.

Such findings differ from those of Swan & Goswami (1997b), which were more clearly in accord with the PRH. In their study group differences, present at all phonological levels in the unadjusted scores, disappeared upon adjustment at the syllable and onset-rime levels, though remained present at the phoneme level. This discrepancy may be due to the dyslexic sample used in this study. In contrast to Swan and Goswami's relatively unremediated sample, twenty of the dyslexic children here were at special schools with a large emphasis on remediating the phonological deficit. This may have resulted in stronger dyslexic group performance and so reduced ability of the phonological measures to sensitively test the PRH.

The pattern of frequency effects across levels was also uneven. If a child has a good phonological representation of a word, as indexed here by the items included within the *adjusted* scores, then whether it is a high frequency or low frequency word should cease to matter on the phonological awareness tasks. A disappearance of frequency effects between unadjusted and adjusted scores occurred on the syllable (long), rime and onset (single consonant) conditions only.

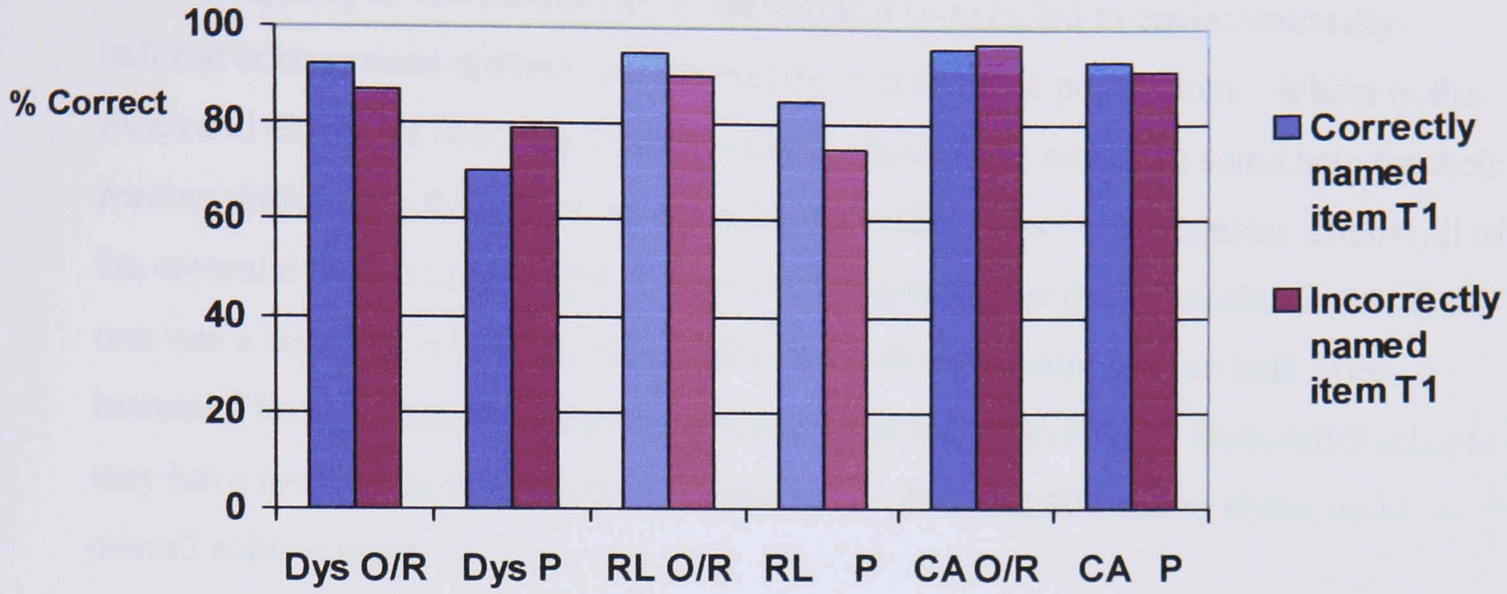
Performance for specific items across levels

To investigate performance on the phonological awareness measures in a more item-specific manner, the cue picture items that featured in more than one task were examined. Taken from the original 40 item picture naming set, 19 of the 20 monosyllabic[7] words were incorporated as cue pictures on two separate occasions - once at the onset (single consonant) or rime level, henceforth 'onset-rime' level and once at the smaller unit, phoneme level (onset - consonant cluster, or coda – single consonant/consonant cluster), henceforth 'phoneme' level. As with the item-specific analyses of the input/output phonological processing tasks, it was of interest to look at performance at different phonological levels, contingent upon adequate representation specificity.

An analysis by child was undertaken. Picture naming performance (from Time 1) was taken as the reference point. For trials within the onset-rime and phoneme level matching tasks that featured the relevant picture items, performance was calculated separately depending upon whether or not the item had been correctly named. Because of the greater risk of ceiling effects for the high frequency items, only low frequency items are displayed. The contingent accuracy scores are shown in Figure 5.7.

[7] The item 'yawn' was omitted from this part of the study due to difficulty incorporating it as a cue picture, with appropriate targets and distracters.

Figure 5.7 Accuracy for selected trials on phonological awareness measures, contingent upon accuracy of picture naming. Performance shown for items at onset-rime (O/R) and phoneme (P) levels. Analysis by child.



Performance was examined in terms of differences between items that had or had not been accurately named in the initial picture naming task. These analyses found no significant differences in performance between correctly and incorrectly named items for any group at any level. This finding is contrary to the predictions of the Phonological Representations Hypothesis, which would presume better performance for items with more specified phonological representations. Again, task sensitivity may be obscuring the true picture of results. As well as overall difficulty level, the presence of two other pictures in each trial (target and distracter) will make it harder to see effects brought about by any single picture item.

5.4 Phase 1 Discussion

The Phase 1 results allow initial conclusions concerning four of the five predictions made at the beginning of this chapter.

Firstly, as hypothesised, the dyslexic children were less accurate at recalling picture names than their CA matched controls, although there was no significant difference in the picture naming scores obtained by the dyslexics and the RL control group. This latter finding does not replicate Swan and Goswami's (1997a) work which found dyslexics performing significantly below their RL controls. One possibility for this discrepancy is that differences in recruitment sources led to environmentally-induced achievement differences between the two dyslexic populations. Whilst in the Swan and Goswami study the children with dyslexia were receiving some help for their reading difficulties, they were not attending specialist schools. In contrast, almost all of the current dyslexic sample (83%) were attending specialist dyslexia schools, of which one was a boarding school (to which 38% of the dyslexic sample attended). The increased levels of acknowledgement, support and help provided by these latter schools may have resulted in elevated motivational levels, learning attribution styles, and overall achievement.

Secondly, the PRH predicts that dyslexic children will have more difficulty with long names, as these require more phonological information to be specified and retrieved from long-term memory, as well as retained in short-term memory. In this study, replicating Swan and Goswami's work, the dyslexic children were the only group to make significantly more errors on pictures with long names than on pictures with short names. In addition, when performance on the naming task was analysed in terms of error type, the dyslexics made significantly more phonological errors than the other groups, as also found in Nation et al. (2001) and Swan and Goswami (1997a). This finding further supports the hypothesis of a phonological basis for the picture naming difficulties of dyslexic children.

Turning to the third prediction, the hypothesis that the dyslexic children's phonological difficulties would contribute to less stable naming performance was supported. The naming responses shown by the dyslexic children were more inconsistent than both other groups: even when the dyslexic children could initially name an item they were less likely to do so on the second occasion, and when making errors at both time points, these were more likely to show variability. This finding replicates the findings of Dietrich & Brady (2001) in their study of dyslexic adults and so suggests an aspect of developmental continuity in the nature of dyslexics' phonological representation deficits. If we assert that a reason for this variability is underspecified phonological representations, then these findings taken together would suggest that this underspecificity can persist long beyond the phases of most rapid phonological representation establishment.

Fourthly, according to the PRH, the performance of dyslexic children on phonological processing tasks based on items for which the phonological representation is well-specified will differ from that when the underlying representation is weaker. In this study, picture naming was used as a basic index of specificity and performance compared to item-matched input, output and phonological awareness tasks. Examination on a word-by-word basis tentatively supports the view that performance involving both input and output phonological processing is contingent upon item-specific representational quality. Furthermore, measures of representational quality have predictive power with regard to concurrent reading ability. Due to the high performance of the chronological-age matched group on many measures, the Phase 1 results do not allow firm conclusions to be made regarding the relative strength of word-specific relationships between groups, however this is an issue addressed further in Phase 2.

5.5 Aims of Phase 2 data collection

The aims of data collection in Phase 2 were threefold. The first aim was to use results from both phases to explore developmental trends and predictive relationships. Of specific interest was the relative rate of progress between groups as well as across tasks – was this progress uniform and if not, what might be accounting for diverging trajectories?

Secondly, due to the relative insensitivity of the picture-matching phonological awareness tasks administered in Phase 1 a more sensitive word-specific phonological awareness task was needed. Because of the challenge of balancing task demand and linguistic level, the decision was taken to focus upon the phoneme level in Phase 2 and to this end a vowel substitution task was devised, described below. Finally, replication was needed of the initial findings suggesting a word-specific relationship between phonological representation quality and performance on phonological processing tasks.

This was achieved through re-administration of the same picture naming task and the associated auditory-visual lexical decision and nonword repetition tasks.

5.6 Phase 2 Methods

5.6.1 Experimental tasks and procedure

Re-administration of measures used at Phase 1

The picture naming task, auditory-visual lexical decision and nonword repetition tasks were re-administered in exactly the same format as at Phase 1. Due to the timing of nationally administered SATS (Scholastic Aptitude Tests) and major structural renovations at one of the participating schools, many children could not be seen for as long as had been possible at Phase 1. For this reason the picture naming task was only administered once at Phase 2. Standardised measures were also re-administered in Phase 2 as reported previously. See Table 5.4.

Vowel substitution task

In this task children were presented auditorily with one of the 40 pictured items, followed by a vowel sound in isolation (the visual image of the picture remained on the screen throughout). The child's task was to substitute the vowels already in the word with the isolated vowel presented and then repeat back the resultant nonword to the experimenter. Following a series of practice items all 40 items were presented in this way and four vowels (two long vowels and two short vowels; all monothongs) were used as substitutes. The words and vowels were both presented through headphones using digitised speech and the children's responses were both transcribed online as well as recorded on minidisc for later offline analysis. A pseudo-random order of presentation was used which always began with three monosyllabic items in order to engender participant confidence early on in the task. A list of the picture names and the vowels presented for substitution is given in Table 5.18.

Table 5.18 Stimulus list - vowel substitution task

Short Length	Vowel	Long Length	Vowel
High Frequency		High Frequency	
dust	æ	exercise	ʌ
clock	u	television	ʌ
flag	ʌ	electricity	ʌ
frame	i	potatoes	æ
pipe	æ	factory	i
queen	u	triangle	u
chain	i	audience	u
globe	u	alphabet	i
tent	ʌ	hospital	i
belt	æ	telescope	æ
Low frequency		Low frequency	
vest	ʌ	propeller	u
quill	æ	protractor	ʌ
claw	i	binoculars	æ
maze	i	harmonica	u
yawn	u	boomerang	i
moat	u	tentacles	æ
harp	ʌ	banister	ʌ
whisk	æ	dominoes	u
wick	ʌ	escalator	æ
clog	i	acrobat	i

Note. /i/ = as in 'beet', /u/ = as in 'boot', /æ/ = as in 'bat', /ʌ/ = as in 'but'

5.7 Phase 2 Results

5.7.1 Picture naming

Accuracy of naming

As in Phase 1, the number of items correctly named for each child was noted and following Katz (1986), any incorrectly named object that was not familiar to the child was eliminated from consideration for that child and the % mean scores computed. These are presented in Table 5.19.

Table 5.19 Adjusted % correct in the picture naming task, Phase 2

	Dyslexic	CA	RL
SL x HF	98.10 (5.12)	98.95 (3.15)	98.57 (3.59)
LL x HF	93.81 (8.65)	98.42 (3.75)	96.19 (7.40)
SL x LF	70.00 (16.12)	74.21 (17.42)	61.90 (14.70)
LL x LF	66.19 (18.57)	82.11 (16.53)	72.86 (19.53)

Note. Standard deviations are in parentheses

The four stimulus classes are Short Length x High Frequency (SL x HF), Long length x High Frequency (LL x HF), Short Length x Low Frequency (SL x LF), and Long Length x Low Frequency (LL x LF).

In order to look at group differences and the effect of contrasting stimuli classes the data was entered into a 3 (reading group) x 2 (length) x 2 (frequency) ANOVA with reading group as the between-subjects factor and with repeated measures on stimulus class length and frequency. The percentage of correct picture naming responses was taken as the dependent variable. The analysis yielded a just significant main effect of reading group, $F(2,58) = 3.04$, $p = 0.05$. Post-hoc tests indicated that the CA controls correctly named significantly more pictures than the dyslexics, $F(1,38) = 4.65$, $p<.05$ and the RL controls, $F(1,38) = 5.15$, $p<.05$. There was no significant difference in the picture naming scores obtained by the dyslexic and the RL control groups. The analysis also yielded a main effect of frequency $F(1,58) = 248.08$, $p<0.001$, though no main effect of length $F(1,58) = 1.07$, $p = 0.31$. Subjects were significantly better at naming pictures with high frequency than with low frequency names (97.30% vs. 70.98% across groups). Although there was no main effect of length, the analysis showed a significant two-way interaction between reading group and length, $F(2,58) = 5.21$, $p<0.01$. Post-hoc testing revealed that the dyslexics were the only group to show the length effect: they were significantly better at naming pictures with short names than long names, $F(1,20) = 5.59$, $p<0.05$.

There was a further interaction between frequency and length $F(1,58) = 12.02$, $p<.01$. Post-hoc investigation found this interaction to be due to frequency having a greater effect upon short length words than long length words, although the size of this effect was still significant in both cases (effect of frequency on short words, $F(1,58) = 236.49$, $p<.001$; effect of frequency on long words, $F(1,58) = 126.72$, $p<.001$).

Error analysis – Phase 2

An analysis of children's erroneous picture naming responses at Phase 2 was undertaken to examine whether the same pattern of errors as seen in Phase 1 would be replicated. For each subject, the number of errors in each category was calculated as a percentage of the total number of errors made. The mean percentage distribution for each group is shown in Table 5.20.

Table 5.20 % Distribution of coded errors on the picture naming task, Phase 2

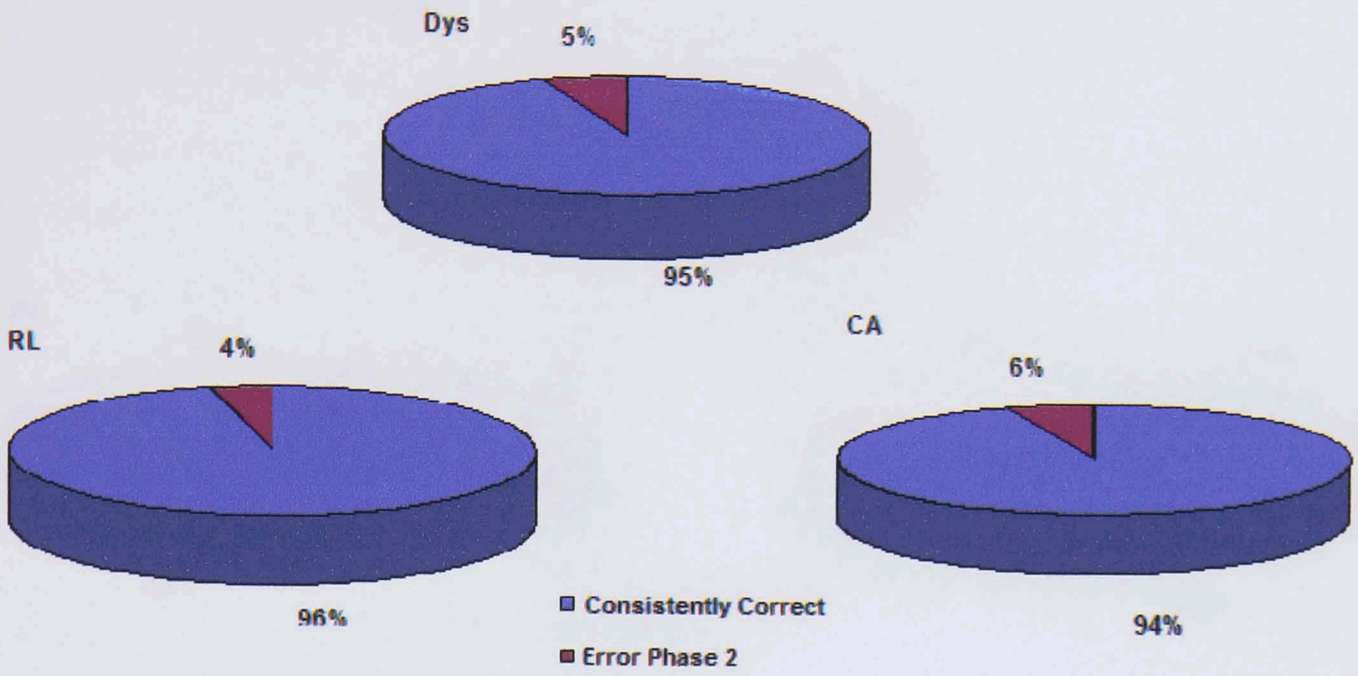
Error Category	Dyslexic	CA	RL
1. Perceptual	1.39	0.58	0.00
2. Semantic	57.49	72.28	64.28
3. Phonological (word)	2.39	1.32	0.53
4. Phonological (nonword)	8.31	1.75	3.89
5. Semantic/Phonological	7.50	11.61	4.13
6. Circumlocution	12.11	8.35	14.50
7. Partial realisation	0.68	0.00	1.70
8. No response	10.13	4.09	10.45

As in Phase 1, the dyslexics had noticeably more phonological nonword errors than the other two groups, as well as an increased number of semantic-phonological errors and circumlocutions. These differences did not reach statistical significance.

Naming consistency

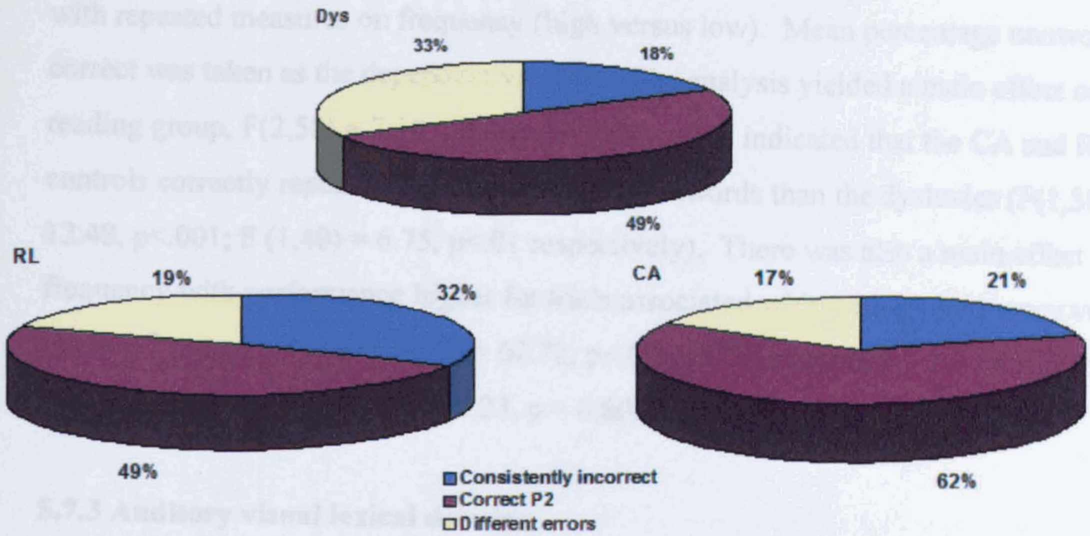
As well as looking at picture naming consistency between the two administrations at Phase 1, it was also of interest to look at naming stability between Phases 1 and 2 for each group. Consistency for correct responses was assessed for each individual by counting the number of correct occurrences at both Phase 1 (Time 1) and Phase 2 for each item. A percentage score, representing the number of words that were correct at Phase 1 and also at Phase 2 (i.e. the number of consistently correct responses) was computed for each individual by dividing the number of these occurrences by the number of correct responses at Phase 1 (see Figure 5.8). There were no significant differences between the groups on the consistency of naming outcomes for items correctly named.

Figure 5.8 Items correctly named at Phase 1 – outcomes at Phase 2



Items incorrectly named at Phase 1 were then examined to determine what proportion of these items were correctly realised at Phase 2 as well as how stable error patterns were. As in the intra-phase 1 analyses 'different' errors were either differences that changed the error category e.g. a phonological error changing to a semantic error, or a difference that did not change the error category e.g. a different semantic substitution made on both occasions. Figure 5.9 displays the group results for this analysis. The CA group showed greater improvement between phases than the other two groups, with 62% of errors at Phase 1 being corrected at Phase 2 (in comparison to 49% for both the dyslexic and RL groups), although these group differences were not statistically significant. It is also notable that the dyslexic group manifested the greatest number of different errors between phases (DYS vs. CA, $F(1,36) = 8.16$, $p<.01$; DYS vs. RL, $F(1,38) = 8.51$, $p<.01$).

Figure 5.9 Items incorrectly named at Phase 1 - outcomes at Phase 2



5.7.2 Nonword repetition

The nonword repetition task was scored in terms of the number of nonwords correctly repeated (out of a total of forty). Group results converted to percentage correct scores are shown in Table 5.21.

Table 5.21 % Nonwords correct in the nonword repetition task[a]

	Dyslexic	CA	RL
HF	85.95 (12.41)	95.00 (6.01)	91.67 (8.27)
LF	71.19 (13.03)	82.63 (11.35)	79.29 (10.99)

Note. Standard deviations are in parentheses

[a] Nonwords derived from High Frequency items = HF and from Low Frequency items = LF.

In order to look at group differences the data was entered into a 3 (reading group) x 2 (frequency) ANOVA with reading group as the between-subjects factor and with repeated measures on frequency (high versus low). Mean percentage nonwords correct was taken as the dependent variable. The analysis yielded a main effect of reading group, $F(2,58) = 7.70$, $p<.001$. Post-hoc tests indicated that the CA and RL controls correctly repeated significantly more nonwords than the dyslexics ($F(1,38) = 12.48$, $p<.001$; $F(1,40) = 6.75$, $p<.01$ respectively). There was also a main effect of frequency with performance higher for trials associated with the high frequency versus the low frequency items ($F(1,58) = 62.72$, $p<.001$). No interaction between frequency and group was found, $F(2,58) = 0.23$, $p = 0.80$.

5.7.3 Auditory visual lexical decision

Accuracy scores are reported in Table 5.22. Accuracy is defined here as the correct detection of a lexical item as well as the rejection of both of the nonword derivatives. Raw scores were thus out of 20, and converted to mean percentages correct.

Table 5.22 % Correct in the auditory visual lexical decision task [a]

	Dyslexic	CA	RL
HF	96.67 (6.58)	100 (-)	98.10 (4.02)
LF	86.19 (21.09)	100 (-)	94.29 (10.28)

Note. Standard deviations are in parentheses

[a] High Frequency (HF), Low Frequency (LF)

In order to look at group differences the data was entered into a 3 (reading group) x 2 (frequency) ANOVA with reading group as the between-subjects factor and with repeated measures on frequency. Mean percentage correct was taken as the dependent variable. The analysis yielded no main effect of reading group, $F(2,58) =$

0.66, $p = 0.66$ or Frequency, $F(1,58) = 0.16$, $p = 0.16$. This was very likely due to ceiling effects for all groups.

5.7.4 Associations between picture naming and input/output tasks

To investigate on a word-by-word basis the relationship between picture naming accuracy and performance on the related AVLD and NWR measures, conditional accuracy scores were again calculated using both a by-item and a by-child analysis.

By item

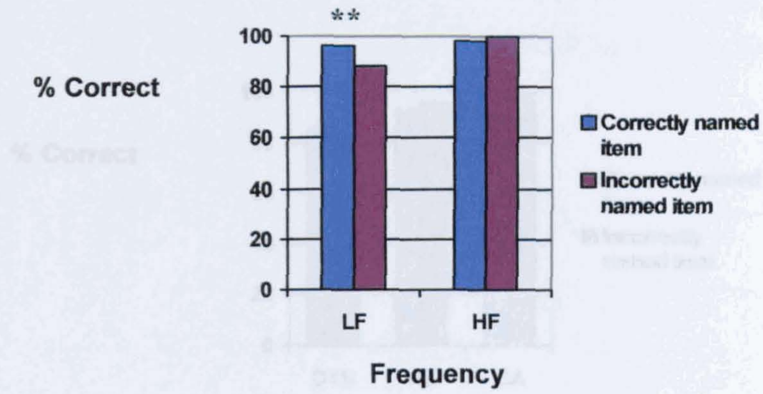
Picture naming performance at Phase 2 was taken as the reference point. Across groups, item performance on the Auditory Visual Lexical Decision and Nonword Repetition (NWR) tasks were assessed and the mean percentage of correct responses was calculated separately for instances where the item had also been named correctly versus instances when the item had not been correctly named.

The contingent accuracy results are shown in Figure 5.10. Asterisks signal a significant difference in accuracy between correctly and incorrectly named items. Low and high frequency items have been analysed separately.

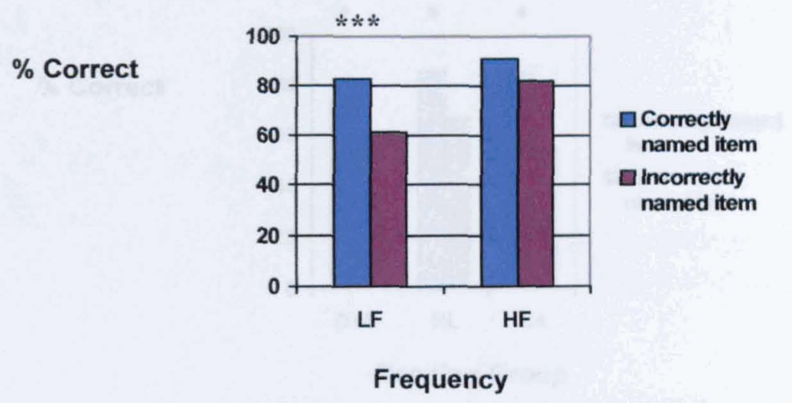
For low frequency items across both tasks there was a significant performance advantage for items that could be correctly named in the picture naming task (AVLD, $F(1,58) = 4.68$, $p<.03$; NWR, $F(1,38) = 24.10$, $p<.001$).

Figure 5.10 Accuracy on a) AVLD and b) NWR tasks, contingent upon accurate picture naming at Phase 2. Analysis by item. * p<.05, **p<.01,***p<.001.

a) AVLD



b) NWR



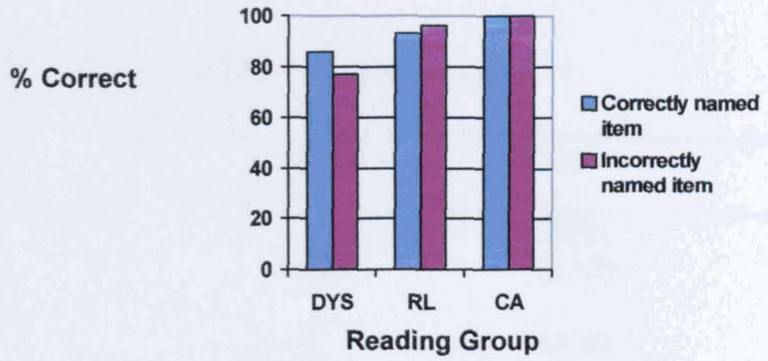
By child

A similar analysis was carried out by child. Accuracy in the AVLD and NWR tasks were separated according to whether a child had also been able to name the item correctly, versus occasions when the item had not been named correctly.

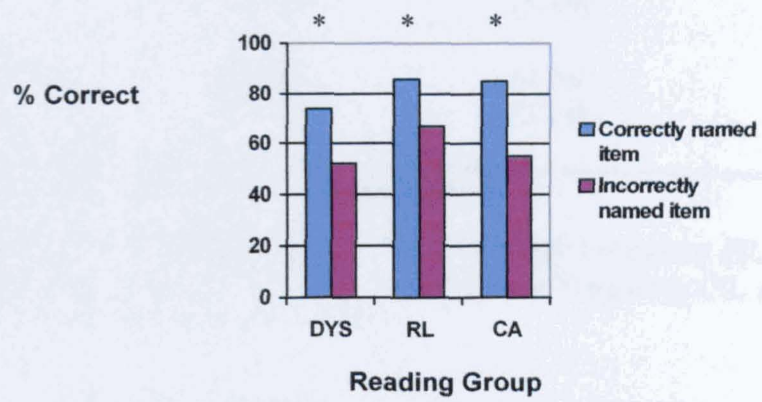
The contingent accuracy scores are shown in Figure 5.11. As in Phase 1, only low frequency items are displayed, due to their greater sensitivity.

Figure 5.11 Accuracy on a) AVLD and b) NWR tasks, contingent upon accuracy of picture naming accuracy at Phase 2. Analysis by child . * p<.05, **p<.01,***p<.001.

a) AVLD: Low frequency



b) NWR: Low frequency



There were no significant differences in performance between the correctly and incorrectly named items in the AVLD task, however in the NWR task these differences were significant for all three groups (DYS $F(1,40) = 6.88$, $p<.05$; CA $F(1,35) = 8.06$, $p<.01$; RL $F(1,37) = 7.41$, $p<.05$).

5.7.5 **Vowel substitution task**

This task was initially scored in terms of the percentage of correctly substituted vowels. Mean percentages correct are presented in Table 5.23.

Table 5.23 % Correct vowel substitutions

	Dyslexic	CA	RL
SL x HF	95.71 (17.48)	98.95 (3.15)	97.50 (4.44)
LL x HF	51.64 (22.42)	65.30 (18.54)	52.50 (29.54)
SL x LF	90.48 (22.69)	98.95 (3.15)	95.00 (16.06)
LL x LF	44.88 (24.54)	61.56 (23.43)	47.00 (26.58)

Note. Standard deviations are in parentheses

The four stimulus classes are Short Length x High Frequency (SL x HF), Long length x High Frequency (LL x HF), Short Length x Low Frequency (SL x LF), and Long Length x Low Frequency (LL x LF).

A qualitative examination of children's overall performance suggested that alternative scoring methods may also prove informative. It was clear that for the polysyllabic words, even children who struggled with this task were managing to substitute at least one vowel within each word. Stronger performance was thus generally associated with the ability to substitute two or more vowels within a polysyllabic word. Polysyllabic results were re-analysed in terms of the number of words (n= 20, 10 high frequency and 10 low frequency) where two or more vowels had been substituted. The mean % scores for this analysis, alongside the unchanged short monosyllabic scores are presented in Table 5.24.

Table 5.24 % Correct vowel substitutions with alternative polysyllabic scoring method

	Dyslexic	CA	RL
SL x HF	95.71 (17.48)	98.95 (3.15)	97.50 (4.44)
LL x HF	55.33 (29.21)	68.95 (23.78)	51.09 (19.14)
SL x LF	90.48 (22.69)	98.95 (3.15)	95.00 (16.06)
LL x LF	40.00 (35.78)	67.37 (28.84)	47.27 (15.90)

Note. Standard deviations are in parentheses

As can be seen, the alternative method of scoring yielded a very similar pattern of results. In order to go on to look at accuracy scores contingent upon correct naming the latter score was deemed more useful. A paired-sample t-test confirmed that the results were not significantly different between the two scoring methods and so with this confirmed, the polysyllabic accuracy results referred to from hereon will be those reported in Table 5.24.

In order to look at group differences the data was entered into a 3 (reading group) x 2 (frequency) x 2 (length) ANOVA with reading group as the between-subjects factor and with repeated measures on frequency and length. Mean percentage correct according to the criteria used in Table 5.24 was taken as the dependent variable. The analysis yielded no main effect of reading group, $F(2, 57) = 1.54$, $p = 0.22$ or frequency, $F(1,57) = 0.04$, $p = 0.82$. There was a main effect of length, $F(1,57) = 44.73$, $p<.001$. As would be expected, across groups accuracy on the monosyllable words was significantly better than performance on the polysyllables (96% vs. 55% respectively). There were no interactions between any of the variables.

Given the mean values given in Table 5.24, especially for the long word length conditions, the lack of significant group differences was somewhat unexpected. Because of this one way ANOVAs were carried out for the LL x LF and LL x HF conditions respectively. These ANOVAs yielded a main effect of reading group for the LL x LF condition only, ($F(2,57) = 4.19$, $p<.05$) with the dyslexic and RL groups performing significantly poorer than the CA group, (DYS vs. CA, $F(1,38)$, = 6.99, $p<.05$; DYS vs. RL, $F(1,37) = 5.27$, $p<.05$). There was no significant difference between the dyslexic and RL group, $F(1,39) = 0.50$, $p = 0.48$.

5.7.6 Associations between picture naming and vowel substitution

To investigate on a word-by-word basis the relationship between naming accuracy and performance on the vowel substitution task, conditional accuracy scores were calculated both by item and by child. Because of the near ceiling performances on the monosyllabic items of this task, only the 20 polysyllabic items are considered here.

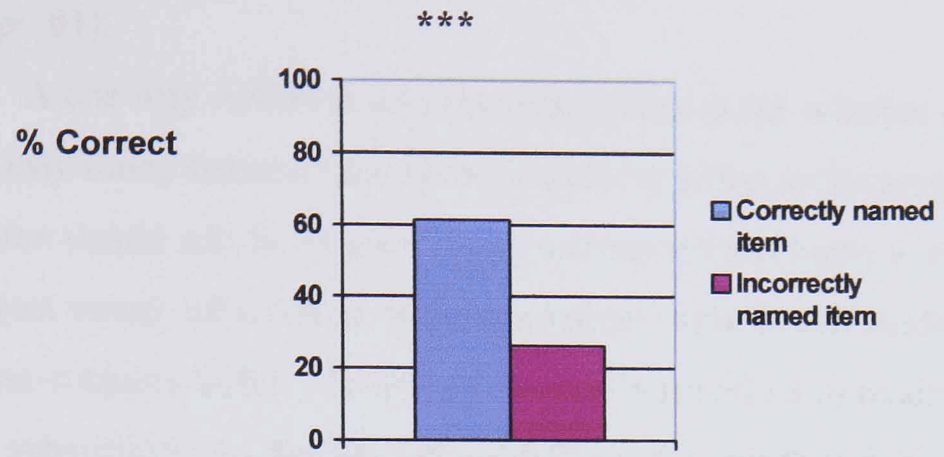
By item

Picture naming performance at Phase 2 was taken as the reference point. Across groups, item performance on the vowel substitution task was assessed and the mean proportion of responses where two of more vowels had been correctly substituted was calculated separately for instances where the item had been named correctly versus instances when the item had not been correctly named.

The contingent accuracy results are shown in Figure 5.12. Low and high frequency polysyllables are combined in this analysis.

There was a highly significant performance advantage for the polysyllabic vowel substitution trials when items had been correctly picture named, $F(1,18) = 33.73$, $p<.001$.

Figure 5.12 Accuracy on vowel substitution task, contingent upon accuracy of picture naming accuracy at Phase 2. Analysis by item for polysyllabic trials. *** p<.001.

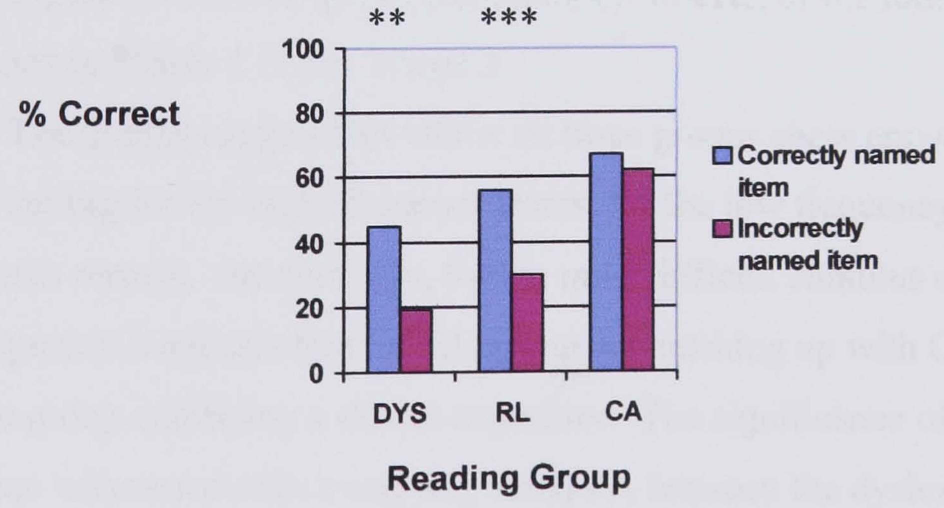


By child

A similar analysis was carried out in the by-child analysis. Accuracy in the vowel substitution task was separated according to whether a child had also been able to name the item correctly, versus occasions when the item had not been named correctly. Group comparisons could then be made.

The contingent accuracy scores are shown in Figure 5.13. To allow comparability with the contingent accuracy analyses for the AVLD and NWR tasks only long length, low frequency items are displayed below.

Figure 5.13 Accuracy on vowel substitution task, contingent upon accurate picture naming at Phase 2. Analysis by child. * p<.05, **p<.01,***p<.001.



For the dyslexic and RL groups there was a significant performance advantage for items that could be correctly named (Dys, $F(1, 39) = 5.23$, $p<.05$; RL, $F(1, 35) = 7.85$, $p<.01$).

A one way ANOVA was also carried out to see whether the group differences previously found between the dyslexic and CA group in the long length, low frequency condition would still be found if only correctly named items were considered. Taking % correct vowel substitution as the dependent variable and reading group as the between-subjects factor. There was now no main effect of reading group on % correct vowel substitution for the hardest condition (long length and low frequency words), $F(2,57) = 2.28$, $p = 0.11$. Post-hoc testing also confirmed that there was no significant difference in performance between the dyslexic and CA groups, $F(1,38) = 3.88$, $p = 0.06$.

5.8 Comparison of Phase 1 and Phase 2 performance

The final analysis of this chapter examined overall performance across groups for the experimental tasks that had been administered during both Phase 1 and 2, picture naming, auditory visual lexical decision and nonword repetition.

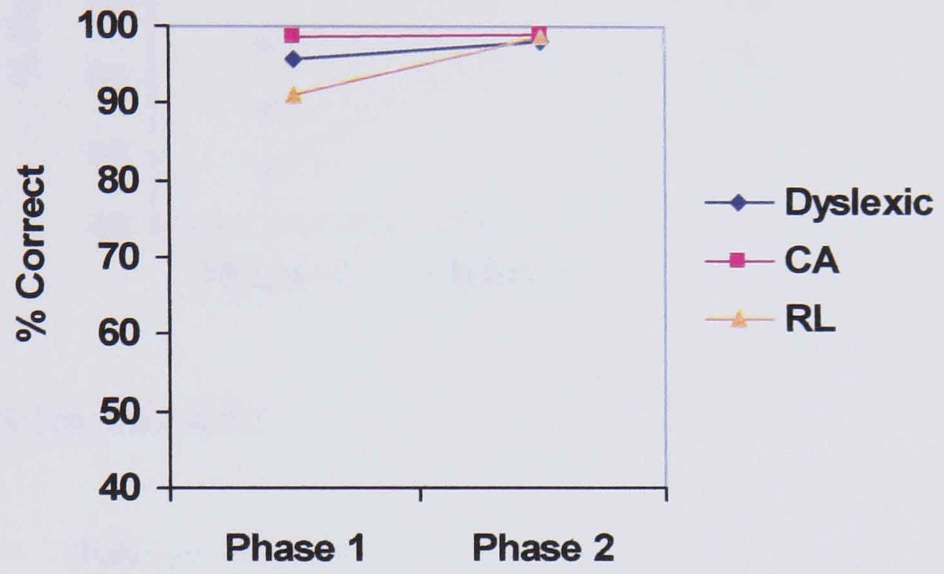
5.8.1 Picture naming

Figure 5.14 shows group performance for each of the four picture naming conditions at Phases 1 (Time 1) and 2.

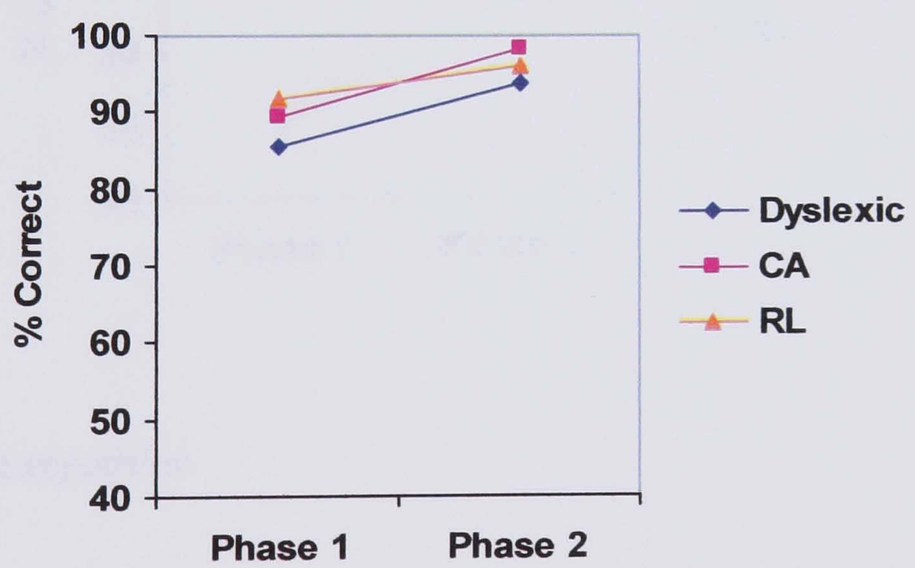
The graphs suggest that whilst all three groups show convergence of scores around ceiling for the high frequency items, for the low frequency items, group differences remain. Interestingly, for the most difficult stimulus class, long length and low frequency it appears that the RL group are catching up with CA controls, with the dyslexic group exhibiting a slower trajectory. The significance of this trajectory difference was tested with a one way ANOVA between the dyslexic, CA and RL groups, taking the degree of change in performance between Phases 1 and 2 for long length, low frequency naming as the dependent variable and reading group as the between-subjects factor. The analysis yielded no significant difference between the groups, F(2,58) = 1.83, p = 0.2.

Figure 5.14 Picture naming performance at Phases 1 and 2

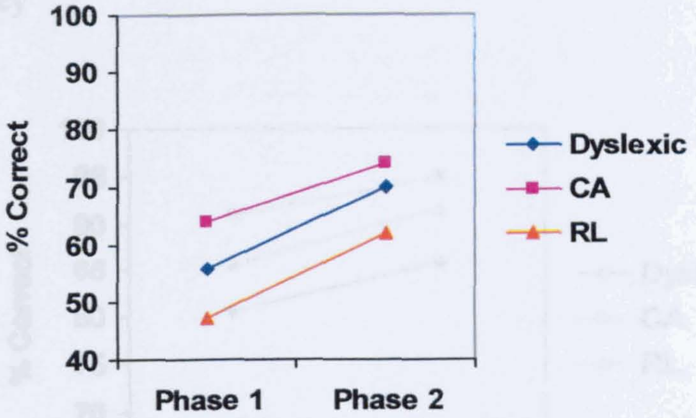
a) Short length x high frequency



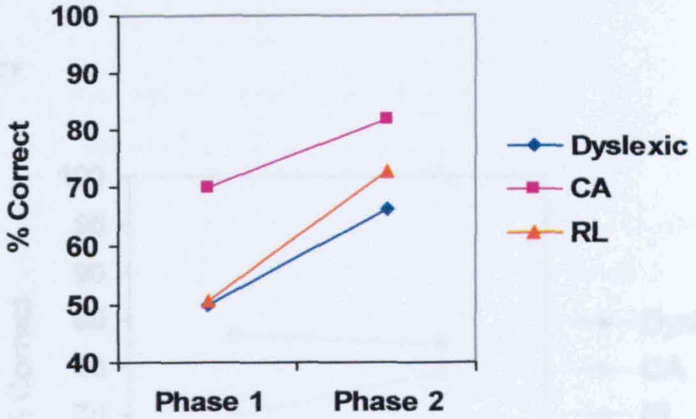
b) Long length x high frequency



c) Short length x low frequency



d) Long length x low frequency

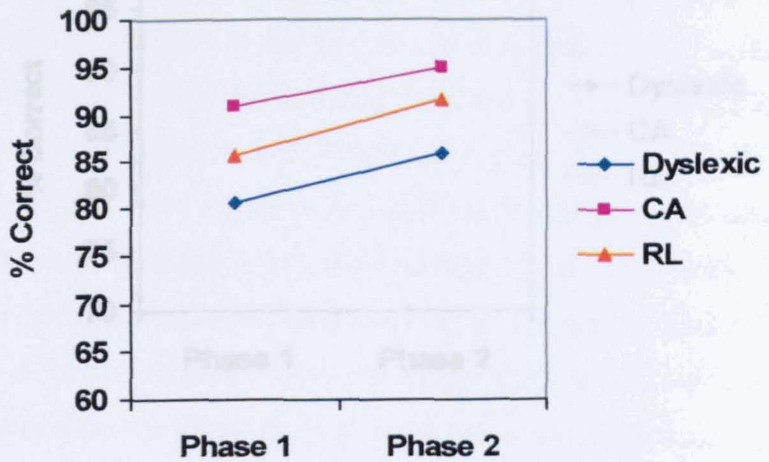


5.8.2 Nonword repetition

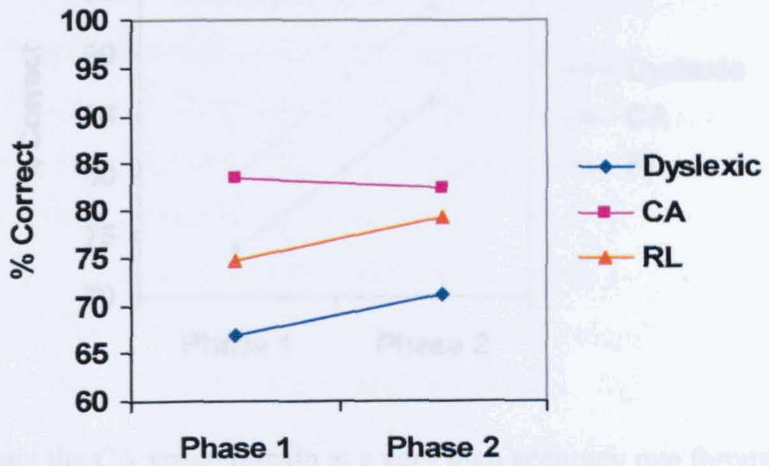
Figure 5.15 shows group performance for the low frequency and high frequency conditions of the NWR task respectively, at Phases 1 and 2. One way ANOVAs found no significant group differences in the degree of Phase 1-Phase 2 change for either the high or low frequency conditions, $F(2,58) = 0.17$, $p = 0.84$ and $F(2,58) = 1.98$, $p = 0.15$ respectively.

Figure 5.15 NWR performance at Phases 1 and 2

a) High frequency



b) Low frequency

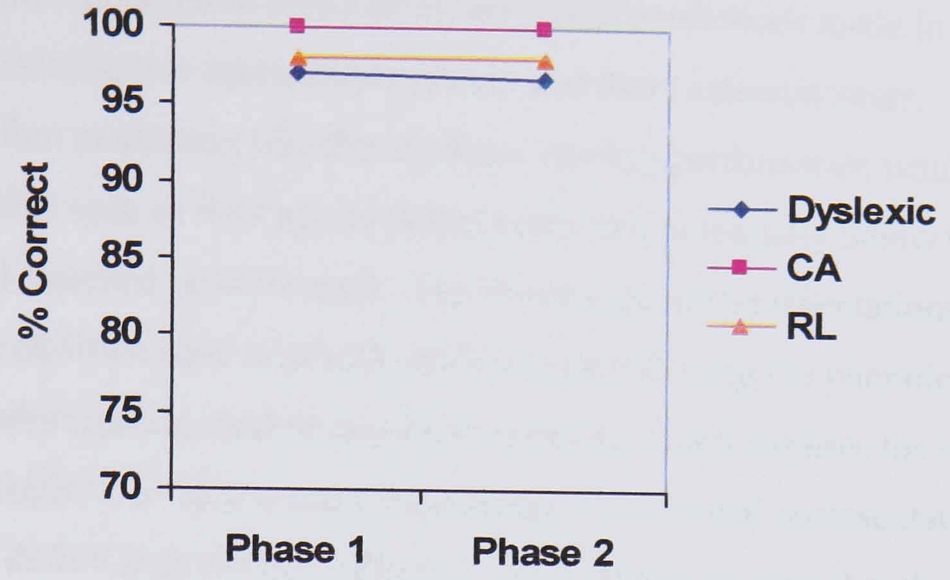


5.8.3 Auditory visual lexical decision

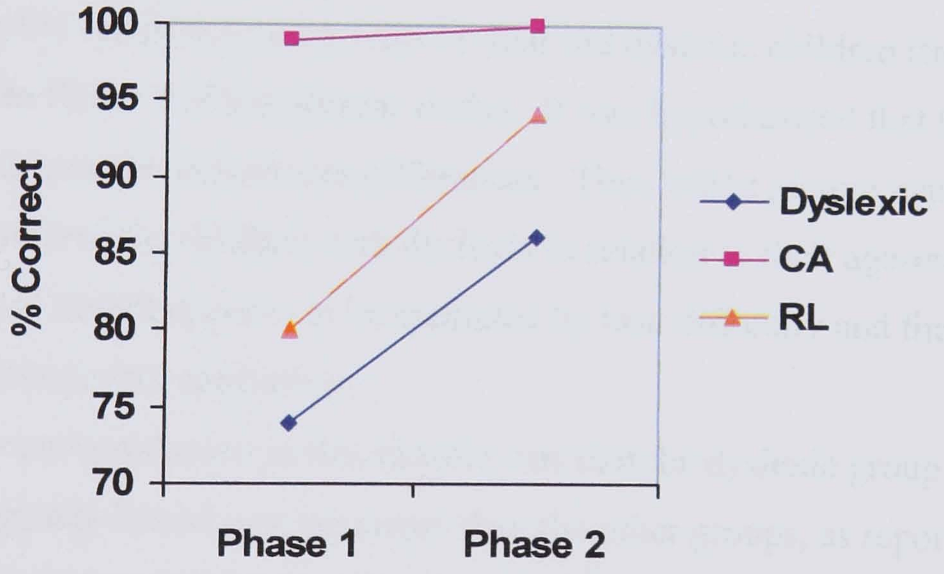
Figure 5.16 shows group performance for the low frequency and high frequency conditions of the AVLD task respectively, at Phases 1 and 2.

Figure 5.16 AVLD performance at Phases 1 and 2

a) High frequency



b) Low frequency



Here again the CA group remain at a very high accuracy rate throughout. A one way ANOVA was carried out for the low frequency scores to determine whether dyslexic and RL groups differed significantly in the degree of performance improvement. This analysis showed that the progress of these two groups did not differ significantly, $F(1,40) = 1.06$, $p = 0.31$.

5.9 Discussion of Phase 1 and 2 results

It is now possible to consider all the initial predictions made in the light of data collection spanning two assessments phases and three calendar years.

The first prediction was that dyslexic naming performance would be significantly poorer than that seen in their age-matched peers and potentially below that of their reading level matched peers as well. The Phonological Representations Hypothesis states that dyslexic children have a specific deficit in establishing the phonological component of lexical representations and so in picture naming, which requires the combined integrity of the phonological, semantic and motor aspects of a lexical representation, a performance deficit is predicted. Phase 1 and 2 results showed that the dyslexic children were significantly poorer than the CA group at picture naming, though on neither occasion did the dyslexics differ significantly from their RL matched peers. As mentioned earlier, this latter result does not replicate Swan and Goswami's findings (1997a) using the same picture set with 11 year old dyslexic children (the average age of the dyslexics in Phase 2 of the present study). It was hypothesised that this discrepancy could be due to sample recruitment differences. Thus whilst picture naming deficits are undoubtedly present for children with dyslexia in relation to their age-matched peers, the absolute level of deficit appears to be mediated by task difficulty and the cumulative effects of environmental mediation.

The second prediction in this chapter was that the dyslexic group would manifest more phonologically-based naming errors than the other groups, as reported by many previous studies (Katz, 1986, 1996; Murphy, Pollatsek and Well, 1988; Rubin & Liberman, 1983; Swan & Goswami, 1997; Wolf & Goodglass, 1986; Wolf & Obregon, 1992). This prediction again stems from the hypothesised phonological representation deficit and this prediction was borne out, with the dyslexic group showing a greater proportion of phonological errors than both other groups at both assessment phases. They were also the only group to exhibit a length effect on naming performance. It is supposed that this is a phonologically mediated effect (Swan & Goswami, 1997a), as naming longer names requires more phonological information to be retrieved from long-term memory as well as retained in short-term memory.

The third prediction of this chapter was that underspecified phonological representations might result in more inconsistent naming performance for dyslexic individuals. To this end the same picture naming task was administered to children twice in Phase 1 and once again in Phase 2. Comparing performance between the two Phase 1 presentations the dyslexic group did show greater naming inconsistency, both in terms of variable accuracy as well as variability *within* error responses. Between Phase 1 and Phase 2 the dyslexic individuals showed greater variability within their error responses only. Interpreting these findings within the framework of the Phonological Representations Hypothesis, one might argue that whilst dyslexic individuals are able to establish the phonological component of their lexical representations at a holistic level, fine-grained phonological underspecificity will result in a more error-prone lexical system.

The fourth prediction laid out at the beginning of the chapter was that for dyslexic children, poor phonological representations, as indexed here by picture naming, would be directly linked to phonological processing difficulties in both input and output tasks dependent upon those representations. Dyslexic children showed significantly better performance on the auditory visual lexical decision task at Phase 1 and the nonword repetition and vowel substitution tasks at Phase 2 for items that could be accurately named. Although task difficulty has an influence on the results here, it appears that both input and output phonological processing are affected by phonological representation underspecificity. This finding concurs with the single case-study report of Constable, Stackhouse and Wells (1997).

A further aim of this chapter had been to examine phonological awareness ability across linguistic levels in relation to phonological representation quality. Swan and Goswami (1997b) found that if representational quality was taken into account when considering phonological awareness performance, group differences between dyslexics and both CA and RL control groups at syllable and rime levels disappeared, although phoneme level deficits persisted. In Phase 1 a replication of these findings was attempted using phonological awareness measures more equated for cognitive demand across levels. However, the picture-match-to-sample task used was basically too easy for the children. In Phase 2 a more challenging vowel substitution task was introduced which focused upon the phonemic level. Performance on this task across groups supported the hypothesis that phonological representation integrity was important for accuracy but furthermore, group differences in the most difficult task condition, long length and low frequency words, disappeared when considering only trials for which children had adequate phonological representations. This result is different to findings of Swan and Goswami (1997b), who found a performance lag at the phoneme level even if only correctly named items were considered. The difference in results may be explainable by the fact that the vowel substitution task used here was challenging to all the reading groups. The high level remediation being received by the dyslexic study sample here may have also been an important factor.

The final prediction of this chapter related to developmental trajectories and predicted that performance in picture naming and the related phonological processing tasks would improve over time for all groups, however the relative rate of progression between groups might vary. Section 5.8 indicated that where ceiling had not been reached on a picture naming condition or phonological processing task, the groups appeared to progress at approximately equal rates. This suggests that dyslexic children are not catching up with their peers and so are reaching secondary school age with persistent deficits in phonological representation specificity. Although the degree of specificity may be increasing over time, the dyslexic individuals still exhibit a consistent lag. It is interesting to note how these results contrast with the Phase 1-2 comparison of reading ability. In this analysis the dyslexic group were progressing significantly more slowly than their age-matched peers, as well as the group originally matched for reading age. This illustration of different skills progressing at different rates emphasises the complexity of developmental trajectories in specific learning disabilities.

Chapter 6 – Phonological neighbourhood density effects in dyslexia

6.1 Introduction

The findings of chapter 5 affirmed the basic suppositions of the Phonological Representations Hypothesis .i.e. the specificity of individual phonological representations determines phonological processing performance in both input and output processing domains. The assessments carried out also highlighted the fact that for all children, some items appear more phonologically specified than others and that lexical factors such as word frequency can influence the degree of specificity attained – word frequency effects favouring high frequency words were consistently observed for picture naming as well as the related phonological tasks across groups.

In chapter 3 phonological neighbourhood density was discussed as an additional lexical factor of importance. Phonological neighbourhood density refers to the number of similar-sounding 'neighbours' any particular lexical item has. Through a range of studies this factor has been shown to influence adult word processing, with sparse phonological neighbourhoods aiding word recognition (Luce & Pisoni, 1998; Vitevitch & Luce, 1998;1999) and dense phonological neighbourhoods facilitating word production (Vitevitch & Sommers, 2003). Similar effects of phonological neighbourhood density have also been reported with children (e.g. Garlock, Walley and Metsala, 2001). This suggests that in a typically-developing as well as a fully-developed lexicon, the phonological properties of words are an important influence upon lexical organisation and processing efficiency.

A goal of this thesis was to explore neighbourhood density effects upon the phonological processing of dyslexic children, with a number of predictions feasible. A prominent idea among researchers is that the presence of many similar-sounding neighbours in the lexicon will precipitate greater phonological specificity in order to differentiate between items. Reduced sensitivity to neighbourhood density may thus hinder phonological specificity and be causally related to the underspecification of phonological representations observed in dyslexia. Alternatively, dyslexics may have normal sensitivity to phonological neighbourhood density and the locus of their phonological representation deficit is elsewhere. A final possibility is enhanced phonological neighbourhood density effects. If dyslexic individuals have compromised phonological representations, making online phonological processing difficult, it could be that they rely more on stored lexical knowledge (despite the underspecified nature of this) when phonological demands are high.

Previous studies of phonological neighbourhood density effects in dyslexic children do not yet allow firm conclusions with respect to these alternative hypotheses. A study of spoken word recognition by Metsala (1997b) yielded ambiguous results that could be interpreted as either an insensitivity to phonological neighbourhood density within the dyslexic group or a particular specification deficit within sparse phonological neighbourhoods as compared to age-matched peers. A subsequent study by Roodenrys and Stokes (2001) looked at short-term memory recall in dyslexic and control children and found equal facilitation effects for high phonotactic probability nonwords across groups (high phonotactic probability correlates with high neighbourhood density).

The aim of the experiments in this chapter was to build upon these findings in several ways. Firstly, phonological neighbourhood density effects would be investigated across several different phonological processing tasks, with phonotactic probability consistently controlled. This would provide multiple contexts with which to explore group differences between the dyslexic children and their controls.

A further goal was to refine the measure of phonological neighbourhood density used. Studies of adults and children have almost exclusively used a one-phoneme difference criterion to define phonological neighbours, yet thinking developmentally this approach can be problematic. Dollaghan (1994) first raised this issue, noting for example, that such a metric results in 'frog' and 'log' not counting as phonological neighbours. Prior to literacy subsyllabic units such as onset and rime may be the most accessible to young children in their development of phonological awareness skills and we also know that rime neighbours, such as 'frog' and 'log' are the most predominant neighbour type amongst English monosyllables (De Cara & Goswami, 2002). Rime neighbourhood density and overall neighbourhood density are also highly correlated.

When trying to understand a developmental difficulty such as dyslexia where the specific problem is achieving phonological competence at the level of the phoneme, exploring similarity neighbourhoods according to phoneme-level differences appears counter-intuitive. For this reason, rime neighbourhoods, less reliant on literacy exposure are investigated here.

6.1.1 Experimental design

As mentioned in chapter 2, there are three classic task areas upon which dyslexic children are shown to have phonological difficulties: short-term memory, phonological awareness and Rapid Automatised Naming (RAN).

It was decided that the experiments of Phase 1 would assess the effects of phonological neighbourhood manipulations in each of these areas.

Phonological neighbourhood effects upon short term memory performance as measured by word/nonword recall has previously only been investigated in adults. Roodenrys and colleagues have carried out a number of experiments (Roodenrys, Hulme, Lethbridge, Hinton & Nimmo, 2002; Roodenrys & Hinton, 2002) that have found for both word and nonword recall, dense phonological neighbourhoods confer a recall advantage. In children only phonotactic probability has been investigated to date, with advantages for high phonotactic probability items seen in both typically-developing (Gathercole, Frankish, Pickering & Peaker, 1999) and dyslexic children (Roodenrys & Stokes, 2001). However, with these results it is not entirely clear whether phonotactic probability or neighbourhood density is driving the effect. Roodenrys and Hinton (2002) carried out a study which suggested that previously reported phonotactic probability effects in recall tasks may in fact be due to the influence of neighbourhood density. Inclusion here of a short term memory task manipulating phonological neighbourhood density whilst keeping overall phonotactic probability constant would offer a valuable developmental perspective to the existing literature.

As a phonological awareness measure, the oddity task as pioneered by Bradley and Bryant (1978) was chosen. This activity can be used to assess rime awareness and involves listening to strings of words and detecting the item that does not rhyme with the others. In a study of typically-developing five-year-old children (De Cara & Goswami, 2003) performance advantages were observed for trials containing dense neighbourhood stimulus items (rime neighbours as well as total neighbours in this case). An advantage for dense item trials was thus predicted here as a normative pattern.

Finally, RAN object and letter naming sets were created in which neighbourhood density was again manipulated. The only known manipulation of phonological neighbourhood density in a RAN task is an unpublished study by McCrory (2002) in which both dyslexic (n=20) and normally-reading university students carried out two RAN conditions, one with object names from dense phonological neighbourhoods and the other with object names from sparse neighbourhoods. McCrory found an advantage for the object set from sparse neighbourhoods, however this effect was only seen in the dyslexic group. It was of interest here to see whether such results would be replicated in children.

6.1.2 Predictions

1. In typically-developing children dense phonological neighbourhoods were expected to confer a processing advantage for the short-term memory and oddity tasks. For the RAN task processing advantages for sparse neighbourhood items could be exhibited.

2. It was predicted that the dyslexic group would perform more poorly than their age-matched peers across all phonological processing tasks. On the basis of the existing literature, no single prediction could be made concerning the effect of the phonological neighbourhood manipulations.

3. By varying a specific type of neighbour, rime neighbours, differential performance effects for items from dense versus sparse neighbourhoods were still expected.

6.2 Phase 1 Methods

6.2.1 Experimental tasks and procedure

Short-term memory – nonword repetition

This task required the recall of spoken nonword CVC triples. There were 10 experimental trials in total divided equally between two list conditions: nonwords from dense rime neighbourhoods and nonwords from sparse rime neighbourhoods. Neighbourhood density information was obtained from an early version of the De Cara and Goswami (DCG) database (De Cara & Goswami, 2002) containing 3619 monosyllabic words. In the selected nonwords the mean rime neighbourhood density (RND) for dense stimuli was 19.60 (standard deviation, henceforth 'SD' 4.64) and the mean RND for sparse stimuli was 6.12 (SD 2.83). The difference in density between list conditions was highly significant, $t(28) = 10.12$, $p < .001$. Within each trial no phoneme occurred more than once and between list conditions the vowel length and range of phonemes was balanced as much as possible. The dense and sparse nonwords did not differ statistically in the number of lead neighbours (sharing onset and vowel, for example, pat - pad), or overall phonotactic probability (measured via summed biphone frequencies based on log frequency-weighted counts, see Vitevitch & Luce, 1998, 1999). The words differed in overall neighbourhood density. Due to the nature of English phonological structure rime neighbourhood density positively correlates with overall neighbourhood density (De Cara and Goswami, 2002) and so the two types of neighbour can be very difficult to dissociate. Attempts to dissociate these two variables are described in the subsequent experiments. The stimulus list employed is shown in Table 6.1.

Table 6.1 Stimulus list - short-term memory task, with International Phonetic Alphabet (IPA) transcription given in brackets

	Dense RND				Sparse RND			
	zick [z ɪ k]	yane [j eɪ n]	mot [m ɒ t]		woss [w ɒ s]	rerd [r ɜ d]	pul [p ʌ l]	
	bock [b ɒ k]	jat [dʒ æ t]	gip [g ɪ p]		fong [f ɒ ŋ]	mib [m ɪ b]	vut [v ʊ t]	
	lod [l ɒ d]	thag [θ æ g]	pess [p e s]		chud [tʃ ʌ d]	jope [j əʊ p]	geb [g e b]	
	wooz [w u z]	feek [f i k]	vap [v æ p]		lish [l ɪ ʃ]	kern [k ɜ n]	sipe [s aɪ p]	
	teed [t i d]	rill [r ɪ l]	shum [ʃ ʌ m]		shof [ʃ ɒ f]	bup [b ʌ p]	heg [h e g]	
	RND	LND	ND	SBF	RND	LND	ND	SBF
Mean	19.60	7.00	30.00	0.007	6.13	8.13	16.86	0.003
	(4.64)	(4.78)	(9.40)	(0.006)	(2.83)	(6.60)	(7.35)	(0.003)

Note. Standard deviations in parentheses

RND = Rime Neighbourhood Density; LND = Lead Neighbourhood Density;
ND = Total neighbourhood density; SBF = Summed biphone frequency

For each trial, a nonword triple was presented by the computer and the child was asked to repeat back what they heard, as clearly and accurately as possible. The children listened to the words through headphones and their responses were recorded using a minidisc recorder.

Phonological awareness - oddity

In this task overall neighbourhood density was kept constant across all trials, whilst rime neighbourhood density was again systematically manipulated.

The task used triples of spoken CVC words, with the child having to select the non-rhyming item. In all trials, the difference was marked by a coda change (e.g. bud, mud, pup). There were twenty experimental trials in total divided equally between two list conditions: words from dense rime neighbourhoods and words from sparse rime neighbourhoods.

Neighbourhood density information was again obtained from the DCG auditory database. In the selected words the mean RND for dense stimuli was 19.43 (SD 2.91) and the mean RND for sparse stimuli was 6.83 (SD 3.35), $t(58) = 11.35$, $p < .001$. The dense and sparse words did not differ in the number of overall neighbours, overall phonotactic probability (measured via summed biphone frequencies based on log frequency-weighted counts, see Vitevitch & Luce, 1998, 1999), spoken word frequency (Celex database; Baayen, Piepenbrock & Gullikers, 1995) written word frequency (Zeno, Ivens, Millard & Duvvari, 1995), or familiarity (Luce and Pisoni, 1998). In controlling the overall ND between list conditions a concomitant was a significant difference in the number of lead neighbours between groups, $t(57) = -8.032$, $p < .001$. This difference arose through the nature of phonological neighbourhoods in the English language, however attempts to control the number of lead neighbours were made in the experiments of Phase 2.

Each word triple was presented by the computer and the child was asked to select the odd word out, saying the word as soon as they knew the answer. Children were told that the odd word would not rhyme with the others. The stimuli were presented through headphones. The experimental session was recorded using a minidisc recorder for later offline analysis. The stimulus list employed is shown in Table 6.2.

Table 6.2 Stimulus list - oddity task

	Dense RND				Sparse RND			
	wag	nag	that		fish	wish	pith	
	cheek	meek	deed		dove	love	buzz	
	zip	nip	chick		bud	mud	pup	
	wake	shake	date		fizz	biz	give	
	rod	nod	shop		loss	moss	toff	
	nick	thick	chit		lid	bid	rib	
	gap	nap	jack		bird	gird	shirt	
	knock	shock	jot		dutch	hutch	budge	
	wheat	cheat	meek		rib	fib	wig	
	gaze	daze	case		pike	like	ripe	
	RND	LND	ND	SBF	RND	LND	ND	SBF
Mean	19.43	5.63	28.70	0.006	6.83	13.89	25.80	0.005
	(2.91)	(2.19)	(3.91)	(0.003)	(3.35)	(5.18)	(6.79)	(0.003)

Note. Standard deviations in parentheses

RND = Rime Neighbourhood Density; LND = Lead Neighbourhood Density;
ND = Total neighbourhood density; SBF = Summed biphone frequency

Rapid Automatized Naming (RAN)

Each child was administered a test of rapid automatized naming, adapted from Denckla & Rudel (1976). 4 sets were used, two object naming sets and two letter naming sets.

For the object naming sets, four familiar and highly picturable objects were chosen for each. One set contained object words from dense rime neighbourhoods and one set contained words from sparse rime neighbourhoods. Neighbourhood density information was obtained from the DCG auditory database. In the selected words the mean RND for dense stimuli was 19.50 (SD 2.38) and the mean RND for sparse stimuli was 8.50 (SD 1.73), $t(6) = 7.47$, $p < .001$. The dense and sparse words did not differ significantly in the number of overall neighbours, overall phonotactic probability, spoken frequency, written frequency or familiarity. Due to the difficulty of balancing overall neighbourhood density whilst manipulating rime neighbourhood density the number of lead neighbours between groups differed significantly t(6) = -11.50, p<.01.

For the letter naming sets, four letters were chosen for each. One set contained letter names from dense rime neighbourhoods and the other, letter names from sparse rime neighbourhoods. In the selected letters the mean RND for dense stimuli was 29.75 (SD 7.81) and the mean RND for sparse stimuli was 3.25 (SD 2.22), t(6) = 6.53, p< .001. Again, the dense and sparse letters did not differ significantly in the number of overall neighbours, overall phonotactic probability, spoken frequency, written frequency or familiarity, however there was a significant difference in the number of lead neighbours between groups (t(6) = 16.25, p<.03) A list of the stimuli used is shown in Table 6.3.

Table 6.3 Stimulus list a) picture and b) letter RAN tasks
a) Pictures

	Dense RND				Sparse RND			
	cake				fire			
	wheel				bus			
	shop				pipe			
	tie				leaf			
	RND	LND	ND	SBF	RND	LND	ND	SBF
Mean	19.50	3.50	31.75	0.003	8.50	10.50	25.75	0.004
	(2.38)	(3.42)	(8.38)	(0.0004)	(1.73)	(8.35)	(4.79)	(0.002)

Note. Standard deviations in parentheses

RND = Rime Neighbourhood Density; LND = Lead Neighbourhood Density;
ND = Total neighbourhood density; SBF = Summed biphone frequency

b) Letters

	Dense RND				Sparse RND			
	Y				M			
	K				F			
	Z				X			
	Q				H			
	RND	LND	ND	SBF	RND	LND	ND	SBF
Mean	29.75	5.25	39.00	0.003	3.25	16.75	22.75	0.004
	(7.81)	(3.78)	(10.71)	(0.002)	(2.22)	(2.50)	(4.57)	(0.007)

Note. Standard deviations in parentheses

RND = Rime Neighbourhood Density; LND = Lead Neighbourhood Density;
ND = Total neighbourhood density; SBF = Summed biphone frequency

The procedure for each set was the same. Children were first shown a card with each of the four items on and were asked to name them in an untimed format, to ensure familiarity. A speeded practice was then administered in which a card with two repetitions of each item (in a random order) was presented and the children were asked to name the items as quickly and accurately as possible. Presentation of the full set then ensued with the same instructions. The time taken to complete the task was recorded using a stopwatch, along with the errors made. This set contained 40 pictures in 5 rows of 8 (i.e. 10 presentations of each item in a variable order). All children were able to name the letter and object names accurately with error rates of less than 1% and so completion time only is considered henceforth.

6.3 Phase 1 Results

6.3.1 Short-term memory (STM) task

Responses were scored in terms of percentage of correct phonemes recalled. The group means and standard deviations are shown in Table 6.4

Table 6.4 % Correct phonemes in the STM task

	Dyslexic	CA	RL	All groups
Dense RND	81.67 (7.79)	89.16 (5.42)	82.59 (8.81)	84.54 (8.09)
Sparse RND	76.30 (12.55)	83.73 (6.66)	77.22 (12.88)	79.15 (11.44)

Note. Standard deviations in parentheses

RND = Rime Neighbourhood density

In order to look at effects of neighbourhood density and group, a 2 x 3 (rime neighbourhood density x group) ANOVA was run by subject (*F1*) and by item (*F2*), taking the mean percentage of correct phonemes as the dependent variable. The analyses showed a main effect of rime neighbourhood density by subject, $F1(1,70) = 23.80$, $p<.001$, $F2(1,28) = 0.12$, $p = 0.73$ and a main effect of group for both subject and item analyses, $F1(2,70) = 6.11$, $p<.01$, $F2(2,56) = 8.72$, $p<.001$. Recall scores were significantly higher for the dense versus the sparse lists (dense RND nonwords = 84.54 % correct, sparse RND nonwords = 79.15 % correct). There was a significant recall advantage in both list types for the CA group over the dyslexic children and their reading level matched peers (CA vs. DYS, $F(1,47) = 13.53$, $p < .001$; CA vs. RL, $F(1,47) = 8.41$, $p.<.01$). The difference in performance for the latter two groups was not significant, although the mean scores of the dyslexic children were lower. The interaction between RND and group was not significant ($F1(2,70) = 0.004$, $p = 0.99$; $F2(2,56) = 2.09$, $p = 0.13$).

To inspect the data further, the proportion of lexicalisation errors was examined. This analysis explored the proportion of errors caused by a child repeating back a real lexical item. The aim was to measure the extent to which children were using unsegmented stored lexical knowledge to help them to perform the task. The proportions of lexicalisation errors are shown in Table 6.5. The other main error type was primarily phonological, either based on the transposition of phonemes within the trials (e.g. 'gip' realised as 'jip') or substitution with an unheard phoneme (e.g. 'gip' realised as 'thip').

Table 6.5 Proportion of lexicalisation errors (%)

	Dyslexic	CA	RL	All groups
Dense RND	68.9 (21.6)	54.4 (22.2)	53.7 (18.2)	57.46 (23.49)
Sparse RND	47.3 (19.8)	43.5 (22.2)	43.1 (17.5)	44.55 (19.52)
Both RND	57.5 (13.3)	49.0 (15.3)	47.3 (16.3)	51.00 (22.48)

Note. Standard deviations in parentheses
RND = Rime Neighbourhood density

A 2 x 3 (rime neighbourhood density x group) ANOVA was carried out with percentage lexicalizations as dependent variable. The analysis demonstrated a main effect of both group ($F(2,70) = 3.51$, $p<.05$) and density ($F(1,70) = 16.20$, $p<.001$), with no interaction ($F(2,70) = 1.82$, $p = 0.18$). More lexicalization errors occurred within dense rime neighbourhood stimulus sets (57.46% of errors within dense rime neighbourhoods vs. 44.55 % of errors within sparse rime neighbourhoods). This suggests that the sparse stimulus sets, with few real word neighbours, yielded a smaller proportion of lexicalisation errors across groups: there are not that many real words to substitute for the nonwords. The dense stimulus sets however, with many real word neighbours, led to more lexicalisation errors by all groups. In addition, the errors of the children with dyslexia contained a significantly higher proportion of lexicalisations than the errors of the other groups (DYS vs. CA, F(1,47) = 5.37, p<.05; DYS vs. RL, F (1,46) = 6.17, p<.05), between whom there were no significant differences, CA vs. RL, F(1,47) = 0.003, p = 0.9.

6.3.2 Oddity task

Performance is presented in terms of mean percent of correct responses. For this analysis, the occasions on which children requested to hear the stimuli again were not regarded as correct (this occurred on 5% of all trials).

Table 6.6 % Correct responses in the oddity task

	Dyslexic	CA	RL	All groups
Dense RND	54.58 (21.05)	74.40 (17.58)	55.45 (13.63)	61.64 (21.47)
Sparse RND	46.63 (20.60)	66.80 (15.74)	53.18 (16.15)	55.21 (20.89)

Note. Standard deviations in parentheses
RND = Rime Neighbourhood density

A 2 x 3 (Rime Neighbourhood Density x Group) ANOVA was run by subject (*F1*) and by item (*F2*), taking the mean percentage of correct responses as the dependent variable. The analyses showed a main effect of rime neighbourhood density by subject, *F1*(1,70) = 7.09, p<.005, *F2*(1,18) = 0.85, p = 0.37 and a main effect of group for both subject and item analyses, *F1*(2,70) = 23.8, p<.001, *F2*(2,36) = 47.58, p<.001. Accuracy scores were significantly higher for the dense versus the sparse lists (dense rime neighbourhood lists = 61.64% correct, sparse rime neighbourhood lists = 55.21% correct). There was a significant accuracy advantage in both list types for the CA group over the dyslexic children and their reading level matched peers (CA vs. DYS, F(1,47) = 42.87, p< .001; CA vs. RL, F(1,47) = 29.74, p<.001). The difference in performance for the latter two groups was not significant, although the mean scores of the dyslexic children were lower. The interaction between RND and group was not significant ($F1(2,70) = 0.63$, $p = 0.54$; $F2(2,36) = 0.66$, $p = 0.53$).

6.3.3 RAN

The results are analysed in terms of the total time taken to name all 40 items and the mean speeds in seconds are presented in Tables 6.7 and 6.8.

Table 6.7 Mean RAN speed (in seconds) for objects

	Dyslexic	CA	RL	All groups
Dense RND	36.56 (8.30)	32.11 (5.69)	36.68 (7.66)	35.08 (7.49)
Sparse RND	37.36 (7.26)	33.01 (6.67)	38.81 (8.30)	36.35 (7.74)

Note. Standard deviations in parentheses

RND = Rime Neighbourhood density

Table 6.8 Mean RAN speed (in seconds) for letters

	Dyslexic	CA	RL	All groups
Dense RND	39.12 (12.59)	26.45 (4.60)	33.49 (6.69)	32.93 (9.97)
Sparse RND	33.67 (9.11)	24.95 (4.70)	29.35 (6.59)	29.26 (7.79)

Note. Standard deviations in parentheses

RND = Rime Neighbourhood density

Letters and objects were analysed separately in two 2 x 3 (rime neighbourhood density x group) ANOVAs by subject, taking mean speed as the dependent variable. Item analyses were not carried out due to the small N.

a) Objects

The analysis for object RAN showed no main effect of rime neighbourhood density F(1,70) = 2.84, p = 0.87, but a main effect of group F(2,70) = 4.37, p<.05. There was a significant speed advantage for the CA group over the dyslexic children and their reading level matched peers (CA vs. DYS, F(1,47) = 5.99, p < .05; CA vs. RL, F(1,47) = 8.41, p.<.01). The difference in performance for the latter two groups was not significant. The interaction between RND and group was not significant, F1 (2,70) = 0.33, p = 0.72.

b) Letters

The analysis for letter RAN showed a main effect of rime neighbourhood density F(1,70) = 16.29, p= 0.001 and a main effect of group F(2,70) = 15.09, p<.001. There was a speed advantage for sparse RND sets and a significant speed advantage for the CA group over the dyslexic children and their reading level matched peers (CA vs. DYS, F(1,47) = 25.82, p < .001; CA vs. RL, F(1,47) = 18.41, p.<.001). The difference in performance for the latter two groups was also significant, with the RL group performing significantly faster than the dyslexic group, F(1,46) = 4.64, p<.05. The interaction between RND and group was not significant F(2,70) = 1.65, p = 0.20.

6.4 Phase 1 Discussion

At the end of Phase 1 preliminary conclusions regarding the chapter's initial predictions could be made.

In terms of phonological neighbourhood density effects in the typically-developing groups, advantages for items from dense rime neighbourhoods were observed for the short-term memory and oddity task. Speed advantages for RAN letter names from sparse rime neighbourhoods were also present. The lack of neighbourhood density effect for rapid *picture* naming across groups was not predicted. The act of picture naming clearly relies on access to phonological representations. A factor such as neigbourhood density, which is in effect borne out of the accumulation of phonological representations should thus be expected to affect performance, as in the letter naming condition.

One possible explanation for the inconsistent RAN effects is the mean neighbourhood density difference within the letter and picture sets respectively. In both cases the difference between the number of dense and sparse neighbours was statistically significant, however the mean difference between the dense RND and sparse RND sets in the letter RAN was 26.5, whereas for the picture RAN it was only 11.0. Although the latter difference is comparable to that reported for the STM and oddity task, it could be that in a RAN task, which also has a heavy task emphasis upon speeded performance, phonological density effects are less robust and so are only visible when the density difference is great.

With respect to group differences, the performance effect of phonological neighbourhood density was present for all groups. There were no interactions between the effects of density and group, which suggests an equal degree of influence. Thus, although not performing at the level of their age-matched peers in any of the phonological tasks presented here, the dyslexic children showed better performance on the STM and oddity tasks when stimulus items were from dense phonological neighbourhoods and faster RAN speeds for letter names from sparse phonological neighbourhoods. This suggests that although the phonological representations of dyslexic children lack specificity at a fine-grained level, they are essentially organized in a typical manner and dyslexic children are sensitive to the global phonological patterns within their mental lexicons. This lack of interaction between neighbourhood density effects and group contrasts with Metsala's findings (1997b) of a specific difficulty for the dyslexic children in recognizing words from sparse phonological neighbourhoods. Metsala suggested that dyslexic children are sensitive to phonological density, but went further in stating that within sparse neighbourhoods dyslexic children manifest a relative reduction in the level of specification achieved when compared to typically developing children. The use of different tasks precludes too many comparisons between the studies, however, the finding here fails to support the idea that different levels of phonological neighbourhood density can be directly associated with overall specification differences between dyslexic children and their controls.

Parallels can be made, however, with the results of Roodenrys and Stokes (2001), who found that dyslexic children showed recall advantages for items with high phonotactic probability (correlated with high neighbourhood density) in the context of overall performance deficits. In the experiments of this chapter overall phonotactic probability was controlled and only neighbourhood density manipulated. Together, these results converge in supporting the idea of dyslexic sensitivity to the phonological characteristics of their lexicons.

Finally, referring to the prediction of phonological neighbourhood effects being more specifically attributable to rime neighbourhood density effects, this was also borne out. In the oddity and RAN tasks overall neighbourhood density was controlled whilst rime neighbourhood density was specifically manipulated across list sets. With this manipulation density effects were observed of an equal or greater magnitude to those in the short-term memory task, where overall neighbourhood density was also manipulated. Although the number of lead neighbours varied significantly across the dense and sparse RND sets in the oddity and RAN tasks, the degree of difference was consistently smaller than the RND differences. This difference trend was a methodological concern, however, and so efforts were intensified in Phase 2 to control the number of lead neighbours between stimulus sets.

6.5 Aims of Phase 2 data collection

In the second assessment phase of the longitudinal study two additional research questions were posed:-

1. Would the basic findings from Phase 1 be replicated in the same group of children two years later? Would developmental changes be detected?

2. What would be found if a word-learning task was introduced that manipulated phonological neighbourhood density – would phonological neighbourhood density advantages be discernible in a task simulating phonological representation *establishment* and would group differences be found between the dyslexic and control groups?

6.5.1 Experimental design

To address the first question the STM and picture naming subtest of the RAN task were re-administered in Phase 2. A word-learning task was introduced to address the second question. A core tenet of the Phonological Representations Hypothesis is that in dyslexia phonological representations have not been *established* to the level of specificity needed for the high phonological demands of literacy. Relating this to phonological neighbourhood density, to see whether differential sensitivity to neighourhood density affects the course of, or indexes the degree of phonological specification, it would be useful to examine its effects when children are learning new lexical items. There is already evidence from typically-developing pre-school children that words from dense phonological neighbourhoods are learnt more rapidly than those from sparse phonological neighbourhoods in both experimental (Storkel & Rogers, 2000; Storkel, 2001) and naturalistic investigations (Storkel, 2004). The resultant question was would we find the same facilitation in dyslexic children?

The simplest prediction would be 'yes', following the results of Phase 1. Alternatively, enhanced effects might be seen. If the phonological representation deficit in dyslexia arises through a difficulty in online extraction of phonological information when initially establishing representations, then in a new word learning situation dyslexic children may rely even more on pre-existing lexical knowledge. In the short term memory task of Phase 1 where online recall of nonwords was needed, the dyslexics did not show an enhanced effect of phonological neighbourhood density.

However, the errors of the dyslexics did contain a higher proportion of lexicalization errors, suggesting an increased reliance on stored lexical knowledge to some degree. A final alternative is that in the challenge of establishing phonological representations, demands outstrip capacities and so dyslexic children are less able to use the lexical knowledge they do have; this would result in reduced phonological neighbourhood effects.

The experimental procedure used to examine new word learning was the paired associate learning, or 'PAL', paradigm. Because the interest here was upon phonological representation establishment specifically (as opposed to e.g. semantic representation establishment) the PAL task in this chapter involved the pairing of novel phonological forms to meaningless, abstract shapes.

It is known from previous studies that dyslexic children have difficulty making new associations between visual and verbal information (e.g. Vellutino and Scanlon, 1989; Windfuhr & Snowling, 2001; Messbauer & De Jong, 2003). Whilst dyslexic children perform at the level of their age peers in learning associations between two visually presented referents (Vellutino, Steger & Pruzek, 1973), when associating a new phonological form with a picture they show consistent deficits (Vellutino & Scanlon, 1989; Vellutino, Scanlon & Spearing, 1995; Windfuhr & Snowling, 2001; Messbauer & De Jong, 2003). No study has yet manipulated phonological neighbourhood density within such a task, and so the results gained from both the typically-developing as well as dyslexic groups here would be informative.

6.5.2 Predictions

1. For the phonological processing tasks being re-administered (STM and RAN), phonological neighbourhood density effects were again expected.

2. In the PAL task facilitatory effects of dense phonological neighbourhoods were predicted in the control groups. It was predicted that the dyslexic children would perform more poorly overall than their CA peers, however, no a priori predictions were made concerning the phonological neighbourhood density effects for this group.

6.6 Phase 2 Method

6.6.1 Experimental tasks and procedure

Short-term memory – nonword repetition

The experiment required the recall of spoken nonword CVC triples. There were 8 experimental trials in total divided equally between two list conditions: nonwords from dense rime neighbourhoods and nonwords from sparse rime neighbourhoods. Neighbourhood density information was again obtained from an early version of the DCG database (De Cara and Goswami, 2002). In the selected nonwords the mean RND for dense stimuli was 15.42 (SD. 3.65) and the mean RND for sparse stimuli was 7.75 (SD 1.82). There was a significant difference between the dense and sparse RND lists, $t(22) = 6.5$, $p< .001$. Within each trial no phoneme occurred more than once and between list conditions the vowel length and range of phonemes was balanced as much as possible. As a methodological improvement on the task used in Phase 1, the dense and sparse nonwords did not differ in the number of overall neighbours, lead neighbours (e.g. pat, pad), spoken frequencies (Baayen et al., 1995), written frequencies (Zeno, Ivens, Millard & Duvvari, 1995), familiarity (Luce and Pisoni, 1998) or overall phonotactic probability (measured via summed biphone frequencies based on log frequency-weighted counts, see Vitevitch & Luce, 1998, 1999). The stimulus list employed is shown in Table 6.9.

Table 6.9 Stimulus list – short-term memory task, with International Phonetic Alphabet (IPA) transcription given in brackets

	Dense RND				Sparse RND			
	kime [k aɪ m]	pess [p e s]	lert [l ɜ t]		hoss [h ɒ s]	gav [g æ v]	wul [w ʌ l]	
	sog [s ɒ g]	fub [f ʌ b]	wooz [w u z]		fong [f ɒ ŋ]	sipe [s aɪ p]	chud [tʃ ʌ d]	
	tob [t ɒ b]	thag [θ æ g]	nade [n eɪ d]		dorse [d ɔ s]	kern [k ɜ n]	shart [ʃ ɑ t]	
	shum [ʃ ʌ m]	yodd [j ɒ d]	vork [v ɔ k]		mon [m ɒ n]	suke [s u k]	vep [v e p]	
	RND	LND	ND	SBF	RND	LND	ND	SBF
Mean	15.4	4.3	21.8	0.004	7.8	6.1	19.8	0.005
	(3.7)	(3.3)	(3.9)	(0.003)	(1.8)	(2.5)	(3.5)	(0.005)

Note. Standard deviations in parentheses

RND = Rime Neighbourhood Density; LND = Lead Neighbourhood Density;
ND = Total neighbourhood density; SBF = Summed biphone frequency

For each trial, a nonword triple was presented by the computer and the child was asked to repeat back what they heard, as clearly and accurately as possible. The children listened to the words through headphones and their responses were recorded using a minidisc recorder.

Object picture RAN

This was administered exactly as in Phase 1 with no change to the procedures. The stimulus pictures were altered however, in order to more carefully control the number of lead neighbours across sets as compared to Phase 1. In the selected words the mean RND for dense stimuli was 21.5 (SD 4.0) and the mean RND for sparse stimuli was 6.8 (SD 3.5), $t(6) = 7.47$, $p < .001$. The revised stimuli are listed in Table 6.10.

Table 6.10 Stimulus list - picture RAN task

	Dense RND				Sparse RND			
	gate				fire			
	wheel				**cup**			
	shop				**bird**			
	tie				leaf			
	RND	LND	ND	SBF	RND	LND	ND	SBF
Mean	21.50	3.75	28.00	0.003	6.75	8.25	23.00	0.004
SD	(4.04)	(3.10)	(3.74)	(0.0008)	(3.50)	(6.18)	(3.82)	(0.001)

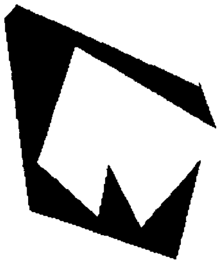
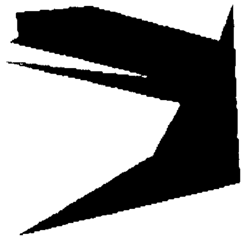
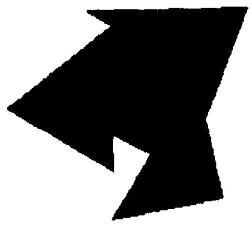
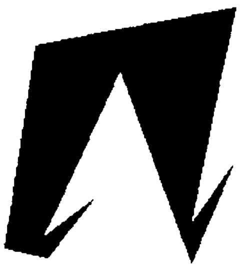
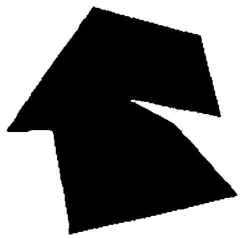
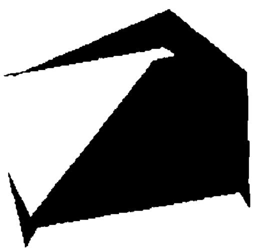
Note. Standard deviations in parentheses
Bold text denotes new stimulus items for Phase 2

RND = Rime Neighbourhood Density; LND = Lead Neighbourhood Density;
ND = Total neighbourhood density; SBF = Summed biphone frequency

Paired associate learning task

This task involved the pairing of 2-D abstract visual shapes with spoken CVC nonwords. Eight shapes were selected from a group of 12-point shapes rated as moderate in complexity and of low associability (Vanderplas & Garvin, 1959). Children were taught to associate these shapes with eight monosyllabic nonwords. Four of the nonwords were selected from dense rime neighbourhoods and four were selected from sparse rime neighbourhoods. Within the respective dense and sparse sets no phoneme was repeated, across the sets vowel length (long versus short) was equated, whilst the range of manner, voicing and place features across sets was also balanced as much as possible. The mean RND for dense stimuli was 17.50 (SD 1.73) and the mean RND for sparse stimuli was 6.75 (SD 3.30), $t(6) = 5.65$, $p < .001$. The dense and sparse nonwords did not differ in the number of overall neighbours, lead neighbours (e.g. pat, pad), or overall phonotactic probability (measured via summed biphone frequencies based on log frequency-weighted counts, see Vitevitch & Luce, 1998, 1999). The stimulus list employed and the associated shapes are shown in Table 6.11.

Table 6.11 Stimulus list - paired associate learning task

Dense RND		Sparse RND	
larse [l ɑ s]		vap [v æ p]	
feg [f e g]		kooz [k u z]	
tib [t ɪ b]		jide [dʒ aɪ d]	
deev [d i v]		wug [w ʌ g]	

	RND	LND	ND	SBF	RND	LND	ND	SBF
Mean	17.50	4.75	23.00	0.004	6.75	8.75	18.50	0.003
	(1.73)	(2.75)	(3.56)	(0.002)	(3.30)	(3.40)	(3.11)	(0.004)

Note. Standard deviations in parentheses.
RND = Rime Neighbourhood Density; LND = Lead Neighbourhood Density; ND = Total neighbourhood density; SBF = Summed biphone frequency

The task was split between two separate assessment sessions and so on each occasion children were introduced to two dense neighbourhood nonwords and two sparse neighbourhood nonwords. The administration format was exactly the same on both occasions and was computer-based. Firstly children were shown the abstract shapes one by one. Alongside the presentation of each shape came a spoken realisation of the associated nonword, presented using digitised speech tokens. Children were asked to repeat the nonword after hearing it and any incorrect realisations were corrected by the tester. This procedure was then repeated once more for each shape. The test trials comprised of 8 blocks. Within each block each of the four abstract shapes was presented in a random order and children were asked to try and recall the name of each of the shapes. After every trial children heard the correct name for the shape irrespective of whether or not they had realised the name correctly. On occasions when children were unsure of the name they were encouraged to guess rather than give a null response.

6.7 Phase 2 Results

6.7.1 Short-term memory task

Responses were scored in terms of percentage of correct phonemes recalled. The group means and standard deviations are shown in Table 6.12.

Table 6.12 % Correct phonemes in the STM task

	Dyslexic	CA	RL	All groups
Dense RND	83.33 (9.14)	87.78 (9.39)	84.39 (12.0)	84.44 (10.19)
Sparse RND	84.25 (8.97)	89.61 (8.67)	83.97 (8.64)	85.83 (8.97)

Note. Standard deviations in parentheses

RND = Rime Neighbourhood density

A 2 x 3 (rime neighbourhood density x group) ANOVA was run by subject (*F1*) and by item (*F2*), taking the mean percentage of correct phonemes as the dependent variable. The analyses showed no main effect of rime neighbourhood density by subject, $F1(1,58) = 0.50$, $p = 0.50$ or item, $F2(1,22) = 4.09$, $p = 0.65$ and a main effect of group for the item analysis only, $F1\ (2,58) = 1.76$, $p = 0.18$, $F2\ (2,44) = 4.09$, $p < .05$. In the item analysis there was a significant recall advantage for the CA group (mean 87.72% correct, SD 6.03) over the dyslexic children (mean 84.33% correct, SD 8.46) and their reading level matched peers (mean 85.45% correct, SD 7.61), CA vs. DYS, $F(1,22) = 5.72$, $p < .05$; CA vs. RL, $F(1,22) = 9.09$, $p < .01$. The difference in performance for the latter two groups was not significant, DYS vs. RL, $F(1,22) = .018$, $p = 0.87$. The interaction between RND and group was not significant ($F1(2,58) = 0.48$, $p = 0.62$; $F2\ (2,44) = 0.87$, $p = 0.43$.

6.7.2 RAN

The results are analysed in terms of the total time taken to name all 40 items and the mean speeds in seconds are presented in Table 6.13.

Table 6.13 Mean RAN speed (in seconds) for objects

	Dyslexic	CA	RL	All groups
Dense RND	33.12 (6.71)	29.78 (5.27)	32.69 (5.65)	31.93 (6.01)
Sparse RND	32.03 (7.56)	27.16 (4.65)	29.36 (5.87)	29.59 (6.40)

Note. Standard deviations in parentheses

RND = Rime Neighbourhood density

To explore the data further a 2 x 3 (rime neighbourhood density x group) ANOVA was undertaken by subject, taking mean speed as the dependent variable. In contrast to Phase 1 the analysis showed a main effect of RND, $F(1, 58) = 9.23$, $p < 0.01$, with the picture set with items from sparse rime neighbourhoods being named more quickly than the picture set selected from dense rime neighbourhoods. The main effect of group just failed to reach significance, $F(2,58) = 3.08$, $p = 0.052$. However, post-hoc analysis revealed that there was a significant speed advantage for the CA group over the dyslexic children (CA vs. DYS, $F(1,38) = 5.79$, $p < .05$). No other group difference reached statistical significance (CA vs. RL, $F(1,38) = 2.97$, $p = 0.89$; DYS vs. RL, $F(1,40) = 0.79$, $p = 0.38$. The interaction between RND and Group was not significant ($F(2,58) = 0.76$, $p = 0.48$.

6.7.3 Paired associate learning

Results were scored in terms of completely correct responses, out of a total of 32 for dense and sparse item sets respectively (8 exposures to each of the 4 paired associations). These scores were converted to percentages correct and are shown in Table 6.14.

Table 6.14 % Correct responses in the PAL task

	Dyslexic	CA	RL	All groups
Dense RND	47.69 (23.62)	87.78 (9.39)	61.46 (18.10)	63.99 (24.32)
Sparse RND	46.28 (28.60)	89.61 (8.67)	53.57 (20.57)	58.35 (26.26)

Note. Standard deviations in parentheses

RND = Rime Neighbourhood density

A 2 x 3 (rime neighbourhood density x group) ANOVA was run by subject[8], taking the mean percentage of correct responses as the dependent variable. The analyses showed a main effect of RND, $F(1,58) = 4.15$, $p<.05$ and a main effect of group $F(2,58) = 15.29$, $p<.001$. Recall scores were significantly higher for the dense versus the sparse sets (dense RND = 63.9% correct, sparse RND = 58.4% correct). There was a significant recall advantage in both density sets for the CA group over the dyslexic children and their reading level matched peers (CA vs. DYS, $F(1,38) = 26.19$, $p < .001$; CA vs. RL, $F(1,38) = 20.30$, $p.<.001$). The difference in performance for the latter two groups was not significant, DYS vs. RL, $F(1,40) = 2.43$, $p = 0.12$, although the mean scores of the dyslexic children were lower. The interaction between RND and group was not significant, $F(2,58) = 0.30$, $p = 0.75$.

An analysis of errors was also carried out. Following initial inspection of the data and using a classification system similar to that of Messbauer and de Jong (2003), three error categories were identified. The first was instances of a wrong association, i.e. a correctly realized nonword associated with the inappropriate abstract shape (henceforth, an 'association' error). The second class was an incorrect realization that phonologically approximated to none of the nonwords (henceforth, a 'phonological' error). The final class was lexicalization errors. A breakdown of the types of errors made as a function of reading group and density is shown in Table 6.15.

In order to explore group and density differences in error type a 2 x 3 x 3 (rime neighbourhood density x group x error type) ANOVA was carried out with group as the within-subjects factor and density and error type as between subject factors. Error proportion was taken as the dependent variable. There was no significant main effect of group $F(2,57) = 0.78$, $p = 0.47$ or density $F(1,57) = 0.73$, $p = 0.4$, however, there was a main effect of error type, $F(2,114) = 13.46$, $p<.001$.

Post-hoc tests revealed that there was a significantly greater proportion of phonological errors across groups than either association errors ($F(1,57) = 12.27$, $p<.001$) or lexicalization errors ($F(1,57) = 40.73$, $p<.001$). There were no significant differences between the proportion of association and lexicalization errors ($F(1,57) = 0.51$, $p = 0.49$).

[8] No item analysis was carried out in this instance due to the small number of items used.

There was also an interaction between group and error type F (4,114) = 3.12, p<.05. Post-hoc testing revealed that the differences in error type were not significant for the CA group (F(2,36) = 1.37, p = 0.27), with the main effect resulting instead from the differences in error proportion of the other two groups (DYS F(2,40) = 4.35, p<.05; RL F(2,38) = 26.79, p<.001).

Table 6.15 % Distribution of coded errors for the PAL task

		Dyslexic	CA	RL	All groups
Association	Dense RND	18.08	20.79	11.84	16.13
	Sparse RND	21.39	30.71	23.79	23.66
	Total	24.68	38.25	17.71	26.75
Phonological	Dense RND	51.02	52.48	68.16	56.68
	Sparse RND	45.83	45.00	56.55	49.06
	Total	47.91	35.42	61.33	48.43
Lexicalization	Dense RND	30.90	26.73	0.20	26.41
	Sparse RND	32.78	24.29	19.66	26.40
	Total	27.41	26.04	20.95	24.82

There was a further interaction between density and error type, F (2,114) = 4.02, p<.05. Post-hoc testing found that this interaction arose because association errors affected a higher proportion of sparse (23.66%) than dense (16.13%) items, whilst phonological errors affected a higher proportion of dense (56.68%) than sparse items (49.06%). Lexicalisations occurred in both sets equally.

The final interaction was that between group and density, F(2,57) = 4.24, p<.05. Post-hoc inspection of the data showed that the interaction arose through the RL group being the only group to show significant differences in the distribution of each error type between dense and sparse items $F(1,18) = 7.12$, $p < .05$

6.8 Phase 2 Discussion

Overall the results in Phase 2 confirmed the findings of Phase 1, though changes in the locus of effect were observed. Re-administration of the short-term memory task this time failed to show any effects of phonological neighbourhood density, though the overall variability in performance between individuals was reduced in Phase 2, which may have reduced the tasks' ability to sensitively show performance effects.

In contrast, re-administration of the picture naming RAN task *did* show effects of phonological neighbourhood density where previously it had not. Concurring with the Phase 1 findings for letters, a speed advantage for the item set selected from sparse phonological neighbourhoods was seen. A likely reason for the appearance of this sparse neighbourhood advantage for the rapid picture naming at Phase 2 was refinement of the stimuli to more carefully manipulate RND only.

The PAL task was introduced at Phase 2 to explore phonological neighbourhood density effects at the point of phonological representation establishment. In this task significant neighbourhood density effects favouring the learning of visual-verbal associations for items from dense phonological neighbourhoods were observed and the effect was the same across groups. This suggests that dyslexic children are as sensitive to the *overall* phonological characteristics of their lexicons as typically-developing children and use this stored knowledge similarly to help them learn new phonological forms; such a conclusion was also backed up by the comparable distribution of error types across groups. The reduced performance of the dyslexic children on this task as compared to their age-matched peers, however, highlights that despite this sensitivity, pervasive phonological representation deficits still exist.

6.9 General Discussion

The main conclusion from this series of experiments is that when neighbourhood density is manipulated in phonological processing tasks, both typically-developing and dyslexic children demonstrate sensitivity to this factor. Despite differences in overall performance levels, with the dyslexic children consistently performing at a level more equivalent to their younger reading level-matched peers, the phonological neighbourhood effects across groups were of equal magnitude. This suggests that despite the underspecified nature of their phonological representations, dyslexic children are organising these representations in essentially the same way as their typically developing peers.

These results are thus broadly in agreement in Roodenrys and Stokes (2001), who reported equal sensitivity in dyslexic and control groups to phonotactic probability. The group differences reported by Metsala (1997b) in a word gating recognition task were not replicated. In a task usually showing processing advantages for lexical items from sparse phonological neighbourhoods, Metsala found that dyslexic children did not show this advantage. Here the only task where a sparse neighbourhood density advantage was predicted was the RAN task and dyslexic performance showed the same sparse neighbourhood speed advantages as the controls. Divergent task demand may explain this discrepancy; further replications of both these results are clearly needed.

Despite the sensitivity to phonological neighbourhood density observed in the dyslexic group, overall performance differences between the dyslexic and CA group were consistently observed. We know that the dyslexic and CA children in this study showed equivalent performance on the WISC vocabulary subtest, however poor performance on the PAL task suggests that the establishment of consistent phonological representations for new referents is delayed for the dyslexics and at an equivalent level to their RL controls.

Chapter 7 – Amplitude envelope onset sensitivity in dyslexia

7.1 Introduction

In chapter 4 the idea was discussed that an underlying cause of the dyslexic difficulty in establishing well-specified phonological representations could be deficits with more basic auditory perceptual processing. This is a much researched field of enquiry and perhaps the current consensus is that although auditory processing difficulties appear associated with developmental dyslexia, the most critical parameters are not yet known and there is not enough evidence that any relationship reported thus far is causal. The viewpoint taken within this thesis is that perhaps we are at this uneasy position because research efforts have been focusing almost exclusively on a small 'grain-size' of auditory processing i.e. a phonemic focus as opposed to also considering the developmentally more primary grain size of the syllable. Amplitude envelope onsets are proposed as a new causal perceptual mechanism to be explored. Amplitude envelope onsets (AEOs) index the relative salience of syllable beats within the speech stream and as such may act as a potent early cue in word segmentation. AEO rise time is a determinant of the salience of each syllable beat and has been shown to correspond to the vowel onset in any given syllable. As a developmental difficulty of sound or phonological representation, dyslexia could feasibly involve a subtle difficulty in processing such amplitude envelope onsets from the earliest developmental stages, which will later manifest as still subtle, but very disabling difficulties in the explicit phonological processing required for literacy competence.

When shifting the causal focus to earlier stages of development it would also appear desirable to assess younger children - in positing the importance of perceptual factors in operation from infancy surely we should be investigating infants. This assertion is undeniably true, yet by doing so we also run into the difficulty of not knowing with certainty which infants will go onto to become dyslexic. Thus, whilst a large-scale prospective study of infants with and without familial risk of dyslexia is a necessary step in determining causality, an important precursor is typifying the importance of potential causal factors in a group of known dyslexic individuals, ideally longitudinally. Such an approach is described in this chapter. It is also advantageous to investigate causal factors in *children* recently identified as dyslexic – this is as opposed to studies of adult dyslexics, where years of behavioural and even neural compensation may have occurred, making causality much harder to attribute (Goswami, 2003).

7.1.1 Experimental design - measuring amplitude envelope onset sensitivity in children

The most recent and comprehensive descriptions concerning the measurement of amplitude envelope onset sensitivity come from the work of Scott (1993; 1998). As reviewed in chapter 4, Scott primarily investigated amplitude envelope onsets via speaker realisations of number counting sequences ("one, two, three…") produced to a regular rhythm (a production task) and the dynamic rhythm setting task (a perceptual task). The latter involves hearing spoken number sequences presented in an asynchronous manner and the use of a potentiometer knob to achieve a perceptually regular sequence.

These tasks were employed with patient adult volunteers and with both tasks there are clear caveats in their application to the behavioural testing of children. Of primary concern is the very large number of trials required for both measures in order to obtain reliable data. A way in which psycho-acousticians have circumvented this problem is the use of adaptive testing procedures, also used here. Using a statistical algorithm, adaptive presentation formats use online performance feedback from the listener to identify the acoustic contrasts causing the most uncertainty in response. Trials then focus around this region of uncertainty until a reliable response profile is achieved. The benefits of this approach are that far fewer trials are required than in non-adaptive presentation formats. As a result, the number of trials contaminated by factors such as attentional lapse are reduced.

As well as mode of presentation, the type of stimuli to be presented to the children required consideration. In Scott's study both non-speech stimuli as well as spoken numbers were used. An adaptive presentation procedure necessitates a continuum of at least forty stimuli varying either linearly or logarithmically along the dimension of interest. The variable found by Scott's empirical work to be especially important within each amplitude envelope onset was the amplitude rise time and so this was the dimension manipulated in the experiments here. It is well known that any speech signal is infinitely complex in its interplay of amplitude, frequency and durational cues and so to be able to isolate the influence of amplitude rise time more specifically, simple non-speech stimuli were used at this stage. The validity of using non-speech stimuli was supported by Scott's findings that amplitude envelope onset cues appeared to operate similarly in both speech and non-speech sounds (Scott, 1993).

The resultant task was a child-friendly categorization game. Children heard a series of amplitude modulated sine-wave sounds, varying in the amplitude rise time of the modulation (the overall rate of amplitude modulation remained constant at 0.7Hz and each stimulus consisted of five continuous cycles). At a slow overall rate of amplitude modulation, varying the rise time of the sound can either induce or take away the perception of a beat within each modulation cycle. With an amplitude modulation rate of 0.7Hz, (i.e. within one second, the sinusoidal wave of the sound completes 70% of its full cycle) a logarithmic continuum of rise times between 15ms and 300ms was possible[9]. Rise times towards the 15ms end of the continuum result in the perception of a discrete beat within the continuously modulating sound. Conversely, rise times towards the 300ms end of the continuum do not yield this discrete beat and so a modulating, but unpunctuated sound is heard. Children were presented with a series of such amplitude modulated sounds and asked to judge whether they could hear a beat or not. The adaptive procedure yielded a numerical slope value for the psychometric function curve fitted to each individual's response pattern. Shallower slopes indicated less sensitivity to variations in amplitude envelope onsets. A category boundary value was also recorded to mark the point at which a child's responses changed from predominantly 'beat' to predominantly 'no beat'. However, due to issues of psychometric validity discussed in the results section of this chapter, this latter value was not analysed further.

[9] Rise times less than 15ms were not used as at such rapid rates a phenomena known as 'spectral splatter' can occur. This can result in the introduction of undesirable, confounding frequency variation.

7.1.2 Predictions

1. If dyslexic children have particular difficulty in extracting information from sound when the AEO change over time occurs more gradually, one would predict flatter slope values of the psychometric function curve (nearer to zero) for this group.

2. In light of the limited previous literature on dyslexic children's auditory performance in relation to their reading-level matched peers and considering the results so far reported in this thesis comparing the dyslexic and RL groups, it was predicted that the dyslexic children would be performing at the same level of these children or below.

3. If dyslexic performance in the AEO detection task was compared to performance on auditory processing tasks used to test the Rapid Auditory Processing Deficit Hypothesis, group deficits were expected for both. However, in claiming a stronger causal link between AEO detection and reading, it was predicted that AEO detection would be more strongly associated with phonological awareness and literacy ability than the other measures.

7.2 Phase 1 Method

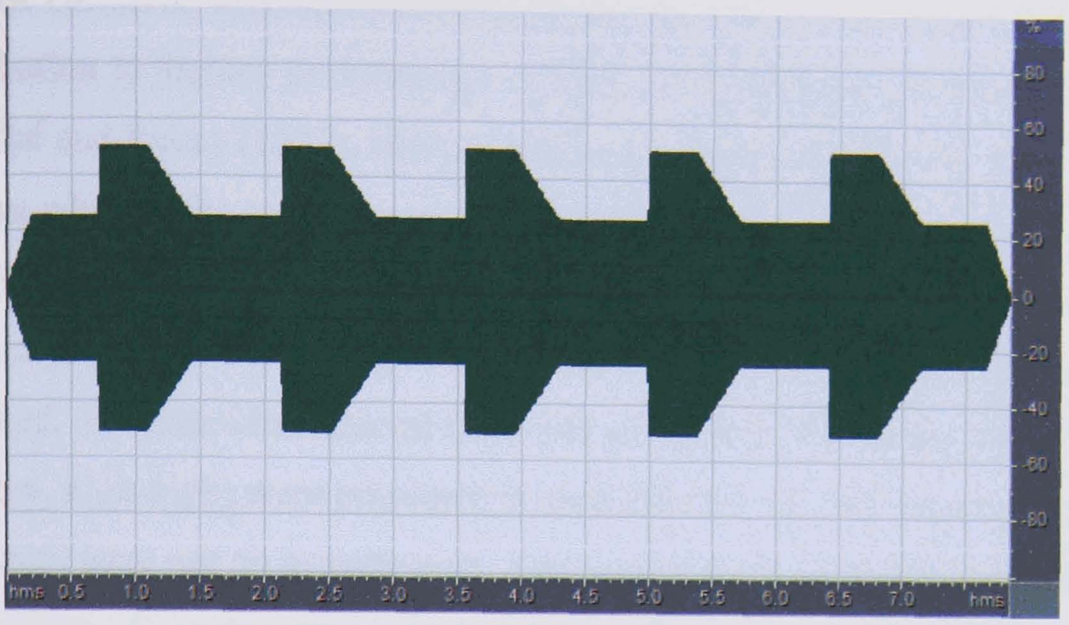
7.2.1 Experimental tasks and procedure

AEO detection task

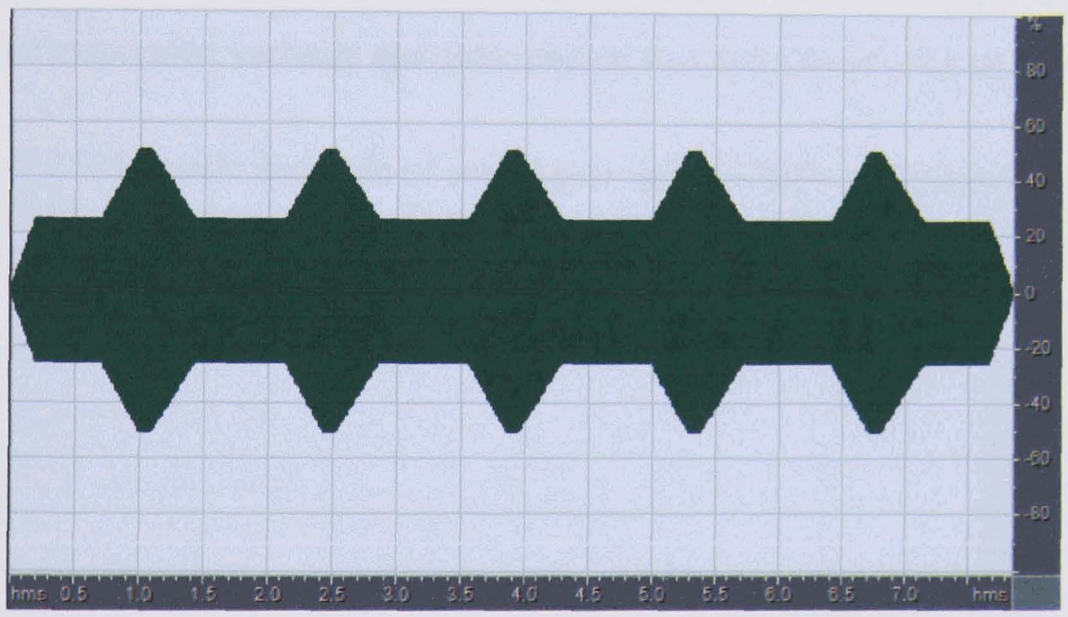
As introduced above, an adaptive psychoacoustic technique was used to assess children's ability to detect differences in amplitude envelope onsets. Continuously modulating sine waves were employed. Each sine wave was 7.9s long, 500 Hz in frequency and modulated in amplitude to a depth of 50% and rate of 0.7Hz (see Figure 7.1). These were presented adaptively via a laptop computer, with the aid of the Speech Pattern Audiometer (SPAII) software devised by Stuart Rosen (Rosen, 2001). In order to help children understand the nature of the task cartoon character toys were introduced and visually associated with sounds that either had a beat or did not. Sounds that did not have a beat were associated with a Winnie-the-Pooh figure, sliding round a bendy straw. This toy was chosen to convey the idea of continuous modulation (through his descent along the circling straw). Sounds that had a beat were associated with a toy in which Tigger and Eeyore were sitting on swings. The researcher demonstrated the characters' movement through a rhythmic swinging motion, conveying an action with more discrete beats than Pooh's motion around the straw. The activity began with a practice period in which the children were introduced to sounds at end points of the continua (three sounds from each end) and these sounds were associated with their respective toy characters. Following this initial exposure the children then heard a further three sounds from each end of the continuum and had to independently decide which toy the sound belonged to. Full feedback was given at this stage and children who were unsure about the task were given further practice as necessary until the researcher was confident that the child fully understood the concepts and procedures involved. The adaptive procedure was then commenced and children heard a maximum of forty sounds, judging each time which toy the sound belonged to. All sounds were presented via headphones and the children's responses were entered into the computer by the researcher. Non-specific, encouraging feedback was given throughout the task and the progress of the activity was paced by the researcher in consideration of each individual child's preferred rate. The adaptive technique used was a modified Levitt procedure (Levitt,1971) and a categorisation function was derived by Probit analysis (Finney, 1971), yielding summary statistics for slope and category boundary.

Figure 7.1 Schematic examples of a) 15ms rise time and b) 300ms rise time stimuli. Time is shown on the horizontal axes in minutes. Amplitude is shown on the vertical axes in %.

a) 15ms rise time



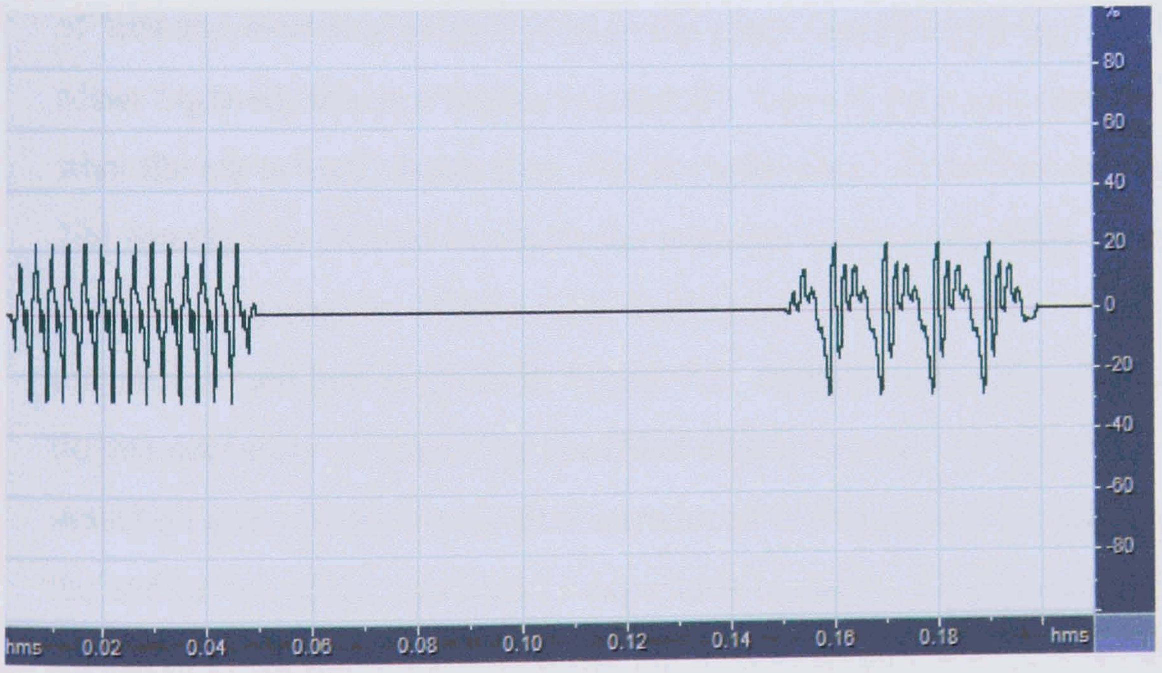
b) 300ms rise time



Rapid Frequency Discrimination task (RFD)

In order to compare performance on the novel AEO detection task with performance on a measure used to test the Rapid Auditory Processing Deficit hypothesis of dyslexia, rapid frequency discrimination (RFD) was assessed. As reviewed in chapter 4, we know that dyslexic children have demonstrated difficulties in carrying out this task, however it is the hypothesis of this thesis that speech cues operating at a larger grain-size, such as the amplitude envelope onset cues of syllable beats, may be an additional, developmentally more primary area of difficulty for dyslexic children. Inclusion of the RFD task thus allowed comparison of the two skills' contribution to literacy performance. Using non-speech stimuli identical to those used by Tallal and Piercy (1973), children were presented with pairs of tones and were asked to judge whether the sounds were the same or different. The stimuli were 50ms complex periodic tones (5ms rise and fall times) with fundamental frequencies of 100Hz and 305Hz. Following four practice trials, 20 experimental trial pairs were presented. Interstimulus interval (ISI) was varied and so four trials (low-low, low-high, high-low, high-high) were presented at each ISI of 0, 10, 50, 100 or 400ms. Because the stimuli were not on a continuum, a non-adaptive procedure was used and trial order was random. Sounds were presented through headphones using the Eurand ASTEC programme (Assessment Test Editor and Controller. Version 3.5.9, Brousseau, 1997). Children responded verbally and their choice was recorded by the researcher.

Figure 7.2 Schematic example of sound pair used in RFD task, high frequency sound leading low frequency sound. Time is shown on the horizontal axes in minutes. Amplitude is shown on the vertical axes in %.

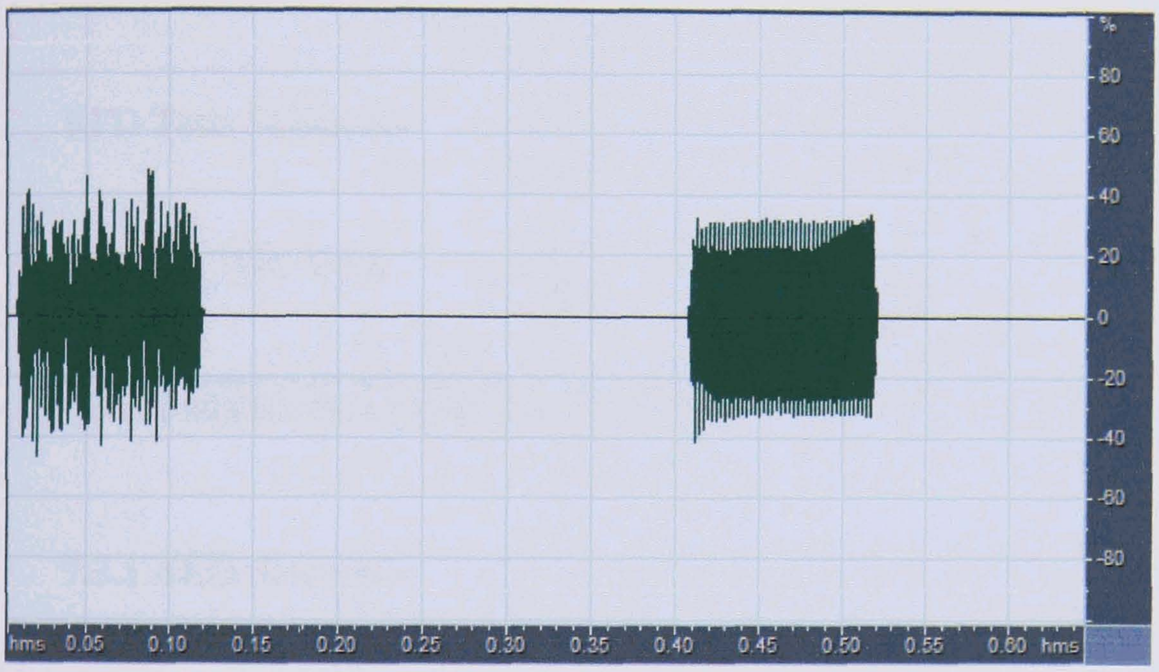


Temporal Order Judgement task (TOJ)

As a further comparison measure with which to test alternative theories of auditory processing in dyslexia a temporal order judgement task was administered. Although subsequently criticised for its conceptual confusion (Mody, Studdert-Kennedy and Brady, 1997), the Rapid Auditory Processing Deficit hypothesis predicts difficulties for dyslexic children with both discrimination of brief and/or rapidly changing stimuli (as assessed by the RFD task above) as well as their temporal order judgment (TOJ). A TOJ measure was thus also included here for comparison purposes. Another advantage of including this TOJ task in the current battery was its adaptive mode of presentation. Thus, if the RFD task, modelled on Tallal's classic study (1980), was lacking sensitivity due to its non-adaptive nature, the slightly revised, yet psychoacoustically more reliable, TOJ task should compensate for this.

Two sounds were presented to the children. These were both non-speech stimuli, readily identifiable as a dog bark and a car horn respectively. Each sound was 115ms in duration. The dog bark was aperiodic whilst the car horn was periodic with a fundamental frequency of approximately 400Hz. Both sounds had a rise and fall time of 5ms and were normalised to have the same overall amplitude level in RMS (Root Mean Squared; this is a loudness intensity measurement unit thought to be closer to what the ear actually hears than, for example, absolute decibel values). A continuum of 204 sounds was created in which the stimulus onset asynchrony varied from +405ms (horn leading dog) to -405ms (dog leading horn) in 4ms steps. A schematic example of one such sound pair is given in Figure 7.3. Stimuli were allowed to overlap to the degree necessary to create the specified stimulus onset asynchronies. As in the AEO detection task children were first introduced to the activity by hearing stimulus pairs at the end points of the continua (3 exposures to each). They then heard three more instances of each in a random order and had to judge for each case whether the dog bark or the car horn was the first sound in the pair. This part of the activity was accompanied by explicit feedback on performance. The adaptive procedure then began and children heard a maximum of forty sound pairs. Each time the children responded verbally by saying which sound they heard first and the researcher recorded the child's responses. All sounds were presented via headphones and the researcher gave non-specific, encouraging feedback. As with the AEO detection task a modified Levitt adaptive procedure (Levitt, 1971) was used and the categorisation function was derived by Probit analysis (Finney, 1971), yielding summary statistics for slope and category boundary.

Figure 7.3 Schematic example of sound pair used in TOJ task, dog leading car. Time is shown on the horizontal axes in minutes. Amplitude is shown on the vertical axes in %.



7.3 Phase 1 Results

A summary of the mean performances by group on the three auditory processing tasks are given in Table 7.1. For the AEO detection and TOJ tasks that were administered adaptively both a category boundary and slope value were yielded. Upon inspection of individual psychometric functions for the AEO detection task, however, it became clear that the presence or absence of a beat as detected by this task was not a categorical percept such as that found for sound contrasts like /b/ vs /p/ (where a very distinctive sigmoidal psychometric function is obtained). Because of this the programme yielded a number of invalid category boundary values. Following discussion with the programme's creator it was decided not to analyse the category boundary values further and so only slope values are reported here. The slope values of the psychometric function curve fitted to the results quantifies how wide the window of response uncertainty is for each child - a shallower slope (value closer to zero) signifies greater uncertainty.

Table 7.1 Mean performances - auditory processing tasks

	Dyslexic	CA	RL
AEO detection: Slope	-0.03 (-0.04)	-0.12 (-0.08)	-0.06 (-0.05)
RFD Task: % correct	75.67 (13.33)	88.64 (10.74)	72.25 (18.17)
Dog/Car TOJ: Slope	-0.03 (-0.02)	-0.04 (-0.03)	-0.03 (-0.02)

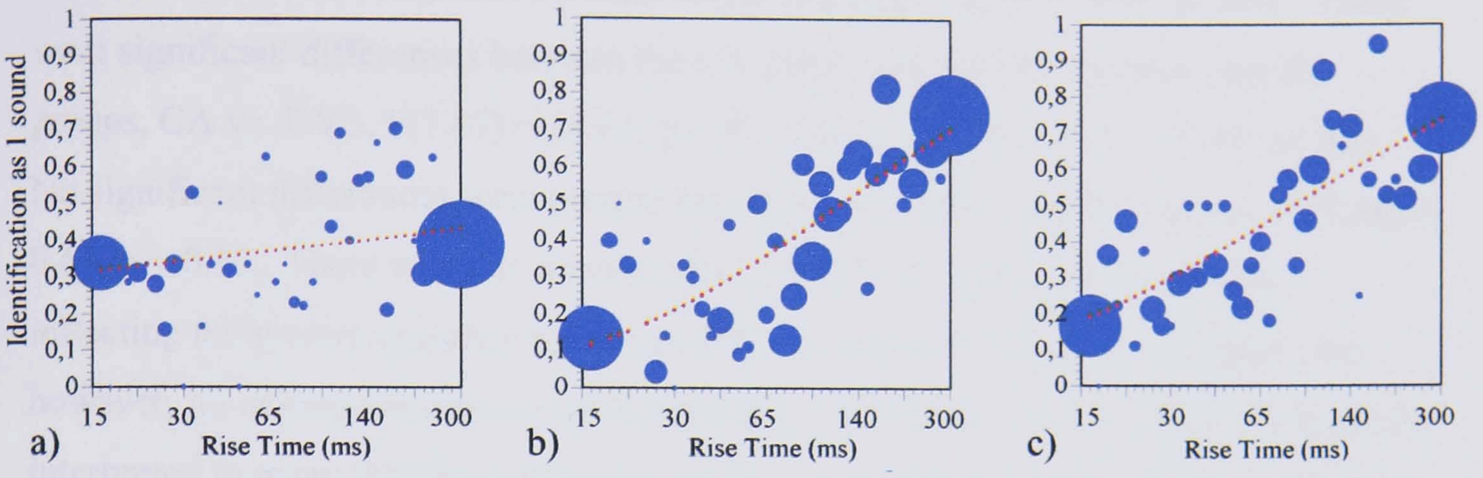
Note. Standard deviations in parentheses

7.3.1 AEO detection

Bubbles plots showing group psychometric functions for the AEO detection task can be seen in Figure 7.4.

Group performance differences were examined using a one way ANOVA. There was a significant main effect of group, $F(2,70) = 13.40$, $p<.001$. Examination of between group differences showed significant differences between the dyslexic and CA groups, with the dyslexics showing flatter slopes as predicted (DYS vs. CA, $F(1,47) = 22.51$, $p<0.001$. The RL group exhibited intermediate slope values, with significantly flatter slopes than the CA group, $F(1, 47) = 8.27$, $p<.01$, however there was no significant difference between the DYS and RL groups, $p = 0.06$.

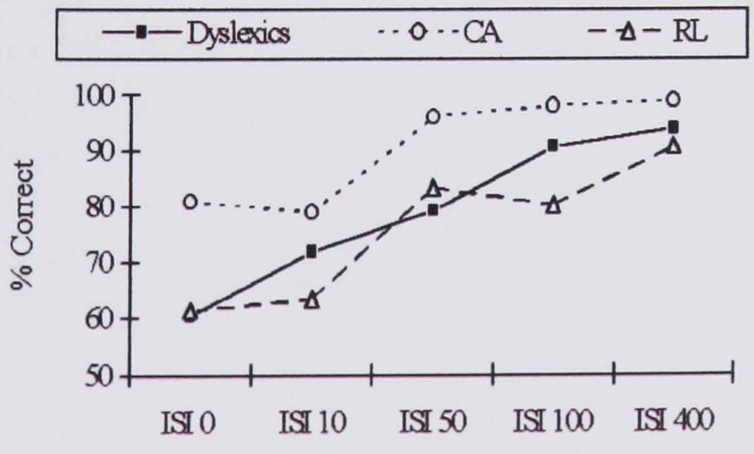
Figure 7.4 Bubble plots of psychometric functions for (a) dyslexic, (b) CA and (c) RL groups - AEO detection task. The size of the bubbles represents the number of trials. Values closer to 1 on the y-axis represent identification judgements of one single modulating sound, with no distinct 'beat'.



7.3.2 Rapid frequency discrimination

The RFD task was not adaptive and so performances are scored in terms of percent correct responses. The RFD results reported in Table 7.1 consider performance for those ISIs below 400ms. Group performances broken down according to ISIs are shown in Figure 7.5.

Figure 7.5 Performance on the rapid frequency detection task (RFD) by group. ISIs are measured in ms.

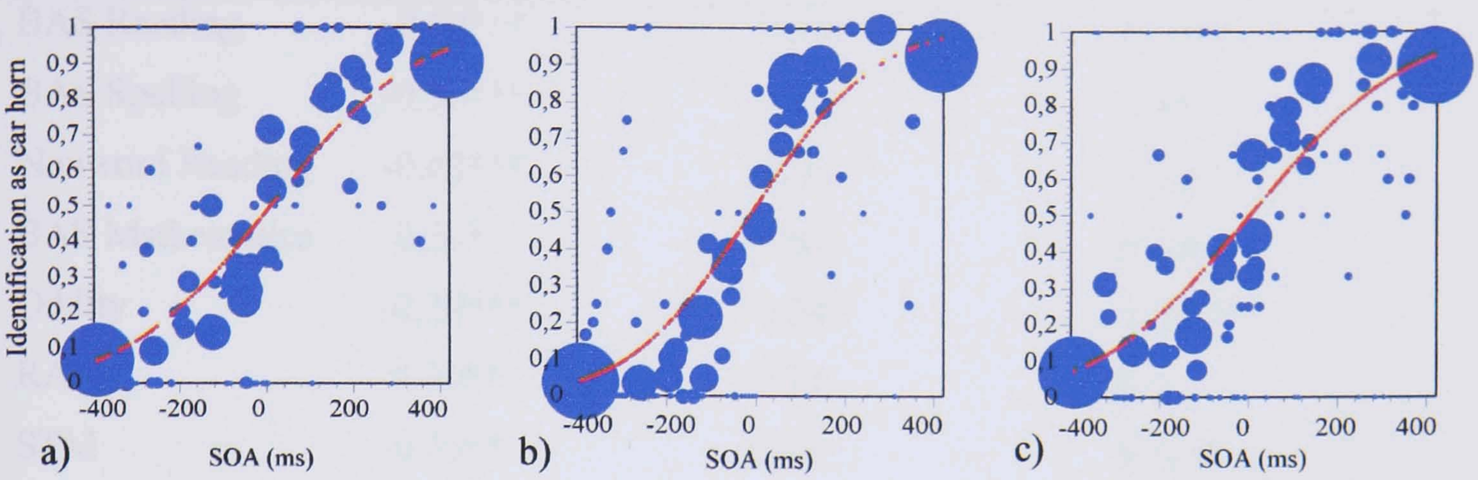


In order to explore the effect of ISI on performance across the groups a 3 x 5 ANOVA was carried out with reading group as the between subjects factor and ISI as the within subjects factor. For this analysis performance at the 400ms ISI was also considered. The results yielded a main effect of group $F(2,70) = 9.08$, $p<.001$. There were significant differences between the CA group and both the dyslexic and RL groups, CA vs. DYS, $F(1,47) = 14.61$, $p<.001$; CA vs. RL, $F(1,47) = 15.30$, $p<.001$. No significant differences were present between the dyslexic and RL groups, $F(1,46) = 0.65$, $p = 0.43$. There was also a main effect of ISI $F(4, 280) = 33.31$, $p<.001$, reflecting the greater accuracy for longer ISIs, as shown in Figure 7.5. There was, however, no interaction between group and ISI, $F(8,280) = 1.41$, $p = 0.19$. This can be interpreted to mean that the performance deficit demonstrated by the dyslexic children in relation to their age-matched peers was constant across both long and short ISIs. This finding differs to that originally reported by Tallal and Piercy (1980), in which the performance deficit was restricted to short ISIs only (below 305ms).

7.3.3 Temporal order judgement (TOJ)

In the TOJ task the slope value again quantified the degree of uncertainty for each child, with shallower slopes indicating less accurate responding. Bubble plots showing group psychometric functions can be seen in Figure 7.6. The data from one RL child was excluded from subsequent analysis due to a programme fault in creating a psychometric fit slope for the child.

Figure 7.6 Bubble plots of psychometric functions for (a) dyslexic, (b) CA and (c) RL groups - TOJ task. The SOA values refer to the stimulus onset asynchrony of the dog in relation to the horn (e.g., -400 ms means the dog barked 400 ms before the horn sounded).



A one way ANOVA found a main effect of group, $F(2,69) = 4.41$, $p<.05$. There was a significant difference in slope value between the CA group and both the dyslexics and RL controls, the CA group showing the strongest performance levels (CA vs. DYS, $F(1,47) = 5.38$, $p<05$; CA vs. RL, $F(1,46) = 6.12$, $p<.05$. There was no significant difference between the dyslexic and RL groups, $F(1,46) = 0.09$, $p = 0.76$.

7.3.4 Relationships between auditory processing, phonological processing and literacy

In order to explore the relationship between the auditory processing measures and phonological processing, reading and spelling, partial correlations controlling for age and WISC IQ (short form) were calculated. These are shown in Table 7.2.

Table 7.2 Partial correlations between the basic auditory processing measures and experimental variables controlling for age and IQ

	AEO detection slope	TOJ	RFD
BAS Reading	-0.59***	0.27*	0.40**
BAS Spelling	-0.56***	0.25*	0.29*
Nonword Reading	-0.43***	0.20	0.42***
BAS Mathematics	-0.34**	0.06	0.24*
Oddity	-0.43***	0.28*	0.40***
RAN	0.36**	-0.12	-0.23
STM	-0.36**	0.25*	0.38**
AEO detection		-0.25*	-0.32**
TOJ	-0.25*		0.45***
RFD	-0.32**	0.45***	

***p< .001, **p< .01, *p< .05

As predicted, there were highly significant relationships between AEO detection and RAN, phonological short-term memory, phonological awareness (as assessed with the oddity task), reading, spelling and nonword reading. There were also significant relationships between the RFD and TOJ tasks and phonological processing and literacy measures although these were less consistent. Both the RFD and the AEO detection tasks showed a significant relationship with mathematical ability, which was not predicted. This result could reflect the short-term memory demands of the mental arithmetic tasks in the standardised mathematical assessment used here.

In order to test this possibility the correlations were re-run, this time partialling out performance on the STM task as well as age and IQ. As can be seen from Table 7.3, with short-term memory controlled, the relationships between maths and auditory processing disappeared, however those between the literacy, phonological processing measures and AEO detection remained. In this analysis the relationship between AEO detection and the other auditory processing measures also disappeared, suggesting that the short-term memory load of tasks accounts for a lot of the associations in Table 7.2.

Table 7.3 Partial correlations between the basic auditory processing measures and experimental variables controlling for age, IQ and short-term memory (STM)

	AEO detection slope	TOJ	RFD
BAS Reading	-0.51***	0.19	0.28*
BAS Spelling	-0.51***	0.19	0.19
Nonword Reading	-0.36**	0.14	0.34**
BAS Mathematics	-0.22	0.06	0.10
Oddity	-0.31*	0.18	0.26*
RAN	0.29*	-0.06	-0.12
AEO detection		-0.18	-0.22
TOJ	-0.17		0.41***
RFD	-0.22	0.41***	

***p< .001, **p< .01, *p< .05

As well as looking at correlational relationships between auditory processing and literacy skills regression analyses can be used to assess to what degree basic auditory processing ability *predicts* concurrent phonological awareness and literacy skill, even when age, nonverbal IQ and vocabulary are controlled. To this end a series of four-step fixed entry multiple regression equations were carried out. For each regression, unusual or influential data-points according to the Cook's Distance (Cook's D) metric were examined. The agreed convention is exclusion of data-points with a Cook's D over 1 (Tabachnik & Fidell, 2001). According to this criteria no data-points required removal for the regression series reported below. The dependent variables were BAS reading, BAS spelling, nonword reading, phonological awareness (oddity), RAN and phonological short-term memory. The independent variables were (in a fixed order) (*i*) age, (*ii*) nonverbal IQ, (*iii*) vocabulary, and (*iv*) an auditory-processing measure (AEO detection, RFD or TOJ). The percentage of variance in the dependent variables explained by the different independent variables is displayed in Table 7.4. Further details for the regression analyses can be found in Appendix 4.

Table 7.4 Percentage of variance in (a) reading, (b) spelling, (c) nonword reading, (d) phonological awareness (oddity), (e) phonological short-term memory (STM) and (f) rapid automatised naming (RAN) explained by the different independent variables in separate fixed entry multiple regression equations. Steps 1, 2 and 3 were always the same (age, nonverbal I.Q., vocabulary). Step 4 was a basic auditory processing variable (AEO detection, RFD or TOJ).

	Dependent Variable (Columns show separate equations)					
	(a) Reading	(b) Spelling	(c) Nonword Reading	(d) Oddity	(e) STM	(f) RAN
	R^2 change	R^2 change	R^2 change	R^2 change	R^2 change	R^2 change
Step 1: Age	0.09**	0.03	0.01	0.00	0.00	0.11**
Step 2: Blocks	0.05*	0.04	0.04	0.13**	0.00	0.05*
Step 3: Vocab	0.11**	0.07	0.02	0.04	0.05	0.00
Step 4: AEO det	0.25***	0.25***	0.14***	0.13***	0.12**	0.08**
Step 4: RFD	0.10**	0.04	0.12**	0.09**	0.13**	0.01
Step 4: TOJ	0.06*	0.05	0.03	0.06*	0.06*	0.00

***p< .001, **p< .01, *p< .05

In order to look at the issue of overlap between the variance in reading accounted for by AEO detection and RFD respectively a pair of five step fixed entry multiple regressions were carried out. The dependent variable in both cases was BAS reading. The independent variables of (i) age, (ii) nonverbal IQ, and (iii) vocabulary were then entered in fixed order followed by the two auditory measures in either order. The percentages of variance in reading accounted for by the respective independent variables can be seen in Table 7.5.

Table 7.5 Percentage of variance in reading explained by the different independent variables in separate fixed entry multiple regression equations. Steps 1, 2 and 3 were always the same (age, nonverbal I.Q., vocabulary). Steps 4 and 5 were AEO detection and RFD in either order.

	DV: BAS Reading, R^2 Change
Step 1: Age	0.09*
Step 2: Blocks	0.05*
Step 3: Vocab	0.11**
Step 4: RFD	0.10**
Step 5: AEO detection	0.19***
Step 4: AEO detection	0.25***
Step 5: RFD	0.04*

***p< .001, **p< .01, *p< .05

Note. DV = Dependent Variable

When entered last, the AEO detection measure accounted for an additional 19% of the variance in reading. The RFD measure entered last accounted for an additional 4%. A large proportion of the variance in reading predicted by the RFD task was thus shared with the AEO detection task but not vice versa.

As a final step, in order to determine whether individual differences in these auditory processing measures would predict reading even when phonological awareness was controlled, a second pair of five step fixed entry multiple regressions were carried out. Once again BAS reading was the dependent variable. The first four independent variables for both regression equations were (i) age, (ii) nonverbal IQ, (iii) vocabulary, (iv) phonological awareness (oddity), with the fifth step as AEO detection or RFD respectively. Percentage of variance values are given in Table 7.6. and further details for each regression can be found in Appendix 4.

Table 7.6 Percentage of variance in reading explained by the different independent variables in separate fixed entry multiple regression equations. Steps 1, 2, 3 and 4 were the same (age, nonverbal I.Q., vocabulary, oddity). Step 5 was AEO detection or RFD.

	DV: BAS Reading, R^2 Change
Step 1: Age	0.09*
Step 2: Blocks	0.05*
Step 3: Vocab	0.11**
Step 4: Oddity	0.30***
Step 5: AEO detection	0.09***
Step 5: RFD	0.02

***p< .001, **p< .01, *p< .05

Note. DV = Dependent Variable

In carrying out this analysis only AEO detection remained a significant predictor of reading, accounting for an additional 9% of the variance. The degree of variance in reading accounted for by the RFD, 2% failed to reach significance (p = 0.08).

7.4 Phase 1 Discussion

At the beginning of this chapter it was predicted that dyslexic children would be less sensitive to amplitude envelope onset variation and that this would be demonstrated through flatter slope values in the psychoacoustic measure used here. This prediction was borne out, with the dyslexic group exhibiting significantly poorer sensitivity to the presence of beats in amplitude modulated sound than the CA controls. In terms of the relationship between AEO detection and the other auditory processing measures used in this study, there appeared to be an overlap in their contribution to the variance in reading, however AEO detection consistently demonstrated stronger predictive relationships with phonological processing and literacy skills.

7.5 Aims of Phase 2 data collection

The Phase 1 results provide preliminary evidence supporting the hypothesis that auditory processing factors operating at the level of the syllable are implicated in developmental dyslexia. But further questions ensued, principally:-

1. What predictive and between group relationships would be found if AEO sensitivity was examined in relation to phonological and literacy ability two years later i.e. longitudinal predictive power?

2. Was the AEO detection task, requiring a categorization judgement, the best way to measure children's sensitivity to amplitude envelope onsets?

3. What could be learnt by looking at within-group as well as between-group variability in amplitude envelope onset sensitivity?

The assessment of auditory processing skills at Phase 2 of the study set out the address these questions.

7.5.1 Experimental design

In order to build upon the results of Phase 1 it was first necessary to reflect upon the sensitivity and specificity of the AEO detection measure used. Although informative as an initial investigation, the very novelty of the measure required that some form of result replication was achieved. Because of time restrictions on the children's availability for research, a re-test had not been possible during Phase 1. Re-administration of the task in Phase 2 would allow performance stability to be examined. For the task to show reliability, significant correlations between children's performance at Phases 1 and 2 would be expected. Changes in performance would allow the presence or absence of a developmental progression to be observed.

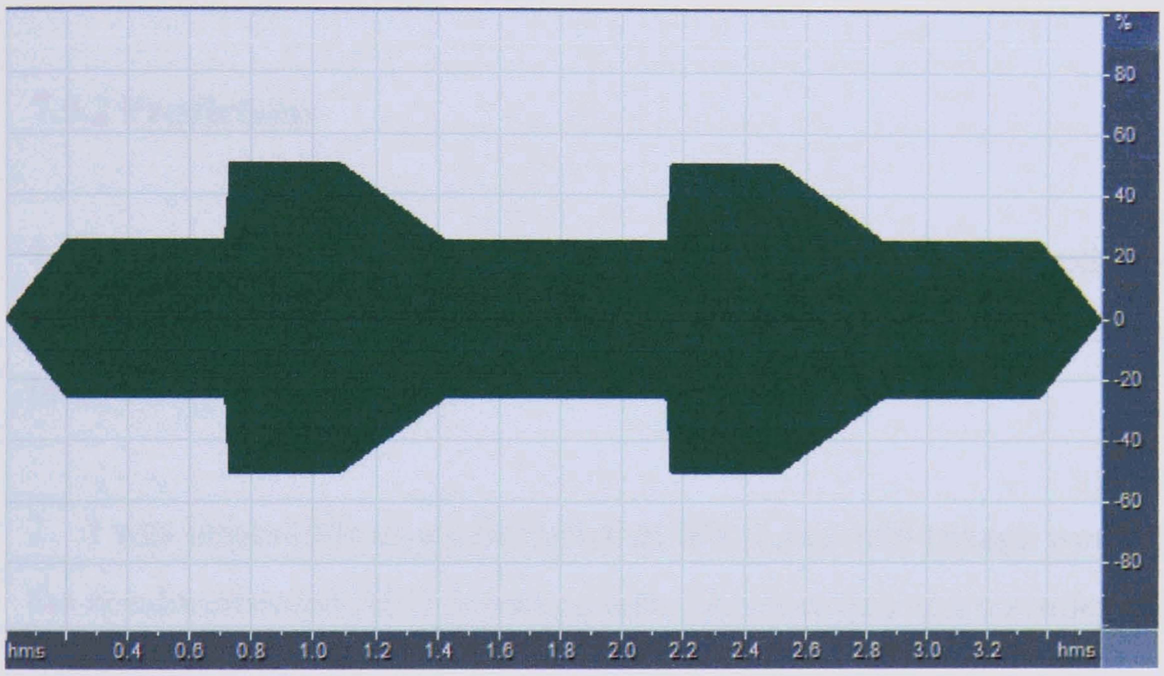
At the same time, it was felt that it might be informative to explore other ways of assessing amplitude envelope onset sensitivity. The use of a categorisation task had clearly highlighted weaknesses in the dyslexic group as compared to their age-matched controls. However, it has also been suggested that categorical perception per se may be a specific area of difficulty for dyslexic individuals (Serniclaes, Van Heghe, Mousty, Carré & Sprenger-Charolles, 2004). In requiring children to make a categorical decision along what was essentially a novel, experimentally-determined continua there would have been the additional cognitive demands of creating end-point sound 'prototypes' at the outset of the task and then keeping these in mind as the task progressed. The latter may also have been aided by a verbal labelling strategy – putting dyslexics at a further disadvantage. In addition, and most importantly, it became clear having administered the task, that beat detection is not a categorical percept. When faced with a continua of sounds such as /ba/ to /pa/ a listener will always hear one or the other, with percepts corresponding to a mixture of the two very rare. With the 'beat' to 'no beat' continua used here such categorical responding was not so obvious. Whilst the slope values obtained can illuminate our knowledge of how consistently children were able to categorise sounds as having a beat or not, it would also be useful to gather converging evidence from a different mode of presentation.

By their very nature, all psychoacoustic procedures will add additional cognitive demands to the auditory perception skill of interest. However, a commonly used procedure for looking at auditory sensitivity in children (which can also be administered adaptively) is the 2IFC (two interval, forced choice) design. In this set-up the listener hears two sounds in each trial. Rather than making a categorical judgment, a comparative judgement is made, for example deciding which sound is higher in pitch, or louder.

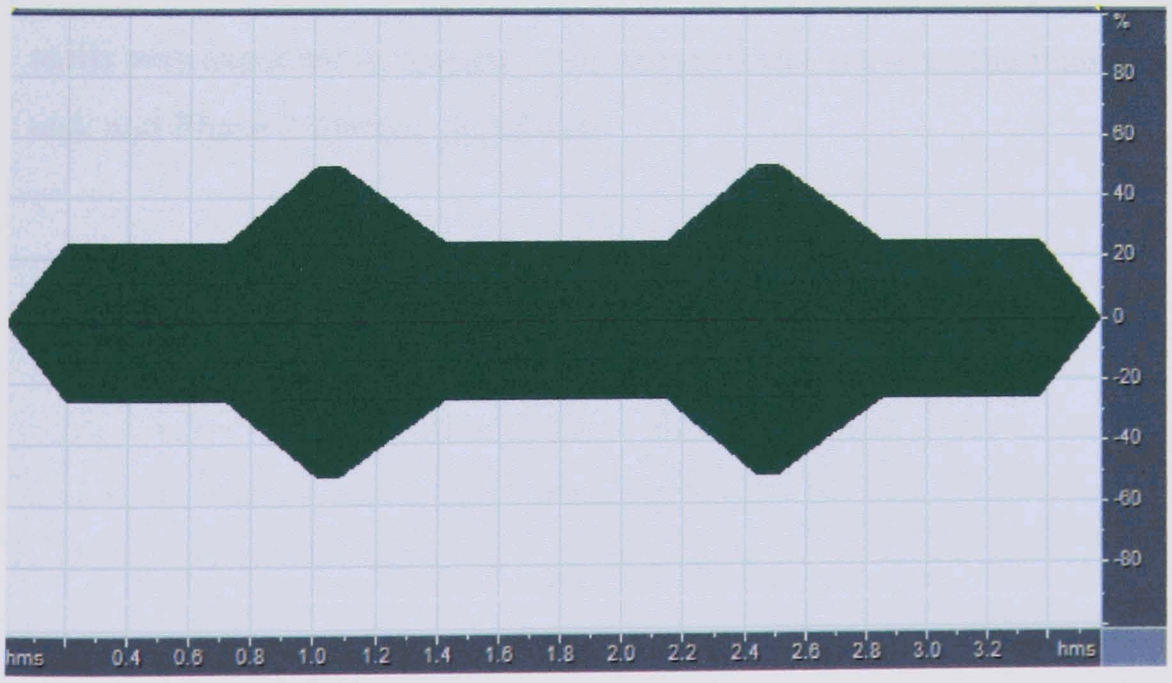
A 2IFC design was used for measuring amplitude envelope onset sensitivity in Phase 2. As in the Rocheron et al. study (2002) this would also allow examination of *discrimination* ability, as opposed to just *detection*. Children were presented with two amplitude modulated sounds of equal modulation frequency and duration, but with different AEO rise times. Their task was to decide which of the two sounds had a sharper beat. Because two sounds were presented, as opposed to just one in the categorisation task, the overall length of the sound stimuli was reduced. This was to avoid excessive demands on working memory, known to be an area of weakness for dyslexic children (Shankweiler, Liberman, Mark, Fowler & Fischer, 1979). The stimuli consisted of two amplitude modulation cycles (see Figure 7.7), whilst the categorisation task used five cycles.

Figure 7.7 Schematic examples of a) 15ms rise time and b) 300ms rise time stimulus. Time is shown on the horizontal axes in minutes. Amplitude is shown on the vertical axes in %.

a) 15ms rise time



b) 300ms rise time



Piloting of the new task with classmates of the children in this study confirmed that two modulation cycles was enough to be able to make the required judgement. The same logarithmic continuum of rise time values was used to create the 40 stimuli set, spanning from 15ms to 300ms.

At Phase 2 it would also have been desirable to re-administer the other auditory measures used in Phase 1 (the RFD and TOJ tasks), however due to restrictions on children's availability for research, this was not possible. Thus, Phase 2 auditory processing assessment involved the original AEO detection task as well as the newly developed AEO discrimination task only.

7.5.2 Predictions

1. It was predicted that the AEO detection deficit seen the dyslexic group at Phase 1 would also be observed in a discrimination task and that performance on these two tasks would be associated.

2. It was impossible to predict whether developmental change would be seen through the re-administered AEO detection task, however this was considered feasible.

3. The concurrent predictive power of amplitude onset envelope sensitivity for literacy skills was expected to remain, with relationships between the Phase 1 AEO detection task and Phase 2 literacy predicted.

7.6 Phase 2 Method

7.6.1 Experimental tasks and procedure

AEO detection task

This task was administered exactly as described for Phase 1.

AEO discrimination task

This 2IFC task was administered using an alternative software programme, created by Dorothy Bishop (2001). In this programme the children were introduced to a pair of cartoon dinosaurs. It was explained that each dinosaur would make a sound and that the child's task was to decide which dinosaur sound had a sharper beat. The concept of beat 'sharpness' was reinforced visually/motorically by the researcher contrasting sharp hand taps on the table with a more gentle brushing contact. The child then participated in five practice trials in which they heard sound pairs and were asked to judge which dinosaur sound had the sharper beat. The sounds were uniformly 3570ms long and presented with an ISI of 500ms. The children were asked to respond verbally by telling the researcher the colour of the chosen dinosaur. As an integral part of this software programme feedback was given after every trial on the accuracy of performance. During the practice period this was accompanied by further verbal explanation and reinforcement by the researcher. The child then proceeded to the main activity. The activity was adaptive and used a more virulent PEST procedure (Parameter Setting by Sequential Estimation; Findlay, 1978) in order to determine how much and in what the direction the stimulus level should be shifted as a result of the child's previous performance. The standard reference stimuli always had the longest rise time value (300ms). The maximum trial number was 40. At the end of the activity a threshold value was yielded which indicated the smallest difference in rise time at which the participant could still discriminate between the two sounds with a 75% accuracy rate.

The AEO detection and AEO discrimination tasks were carried out in separate testing sessions for each child. The order in which the two were given was counter-balanced across children.

7.7 Phase 2 Results

A summary of the mean performances across groups for both tasks is shown in Table 7.7. One RL child was excluded from the AEO detection analysis as his slope value (-1.409) fell almost 22 standard deviations above the RL group mean, i.e. an exceptionally good score.

Table 7.7 Mean performances - AEO detection and discrimination tasks

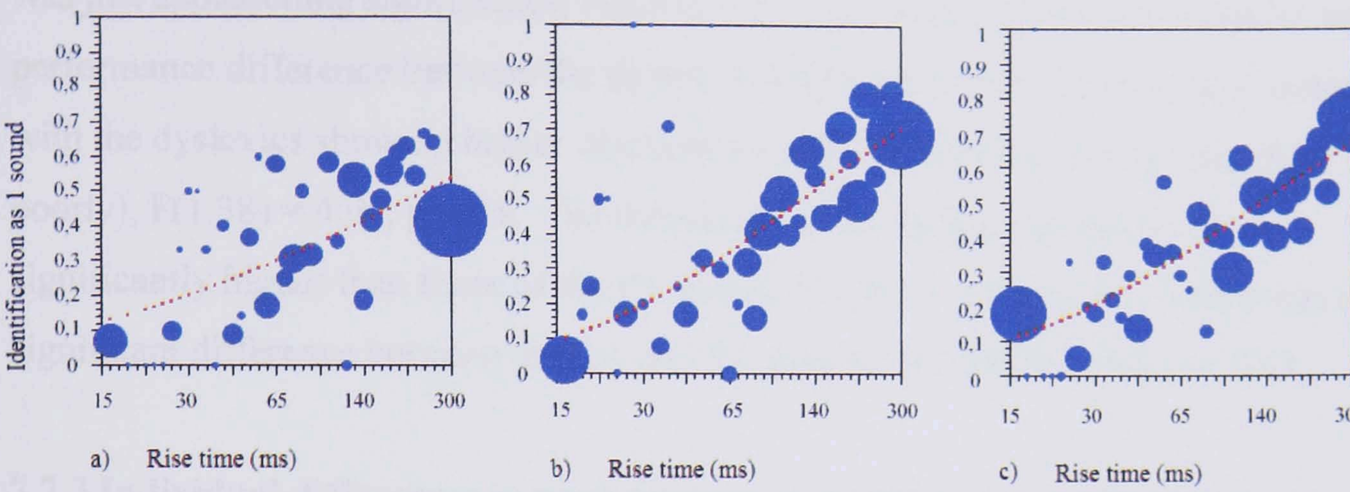
	Dyslexic	CA	RL
AEO detection: Slope	-0.13 (0.12)	-0.15 (0.13)	-0.11 (0.06)
AEO discrimination: Threshold (max = 40, 300ms std)	23.63 (11.00)	16.93 (9.93)	16.31 (11.25)
Range[a] in ms	15-47	15-81	15-87

Note. Standard deviations in parentheses
[a] Range of rise times reliably distinguished from the standard (on 75% of occasions).

7.7.1 AEO detection

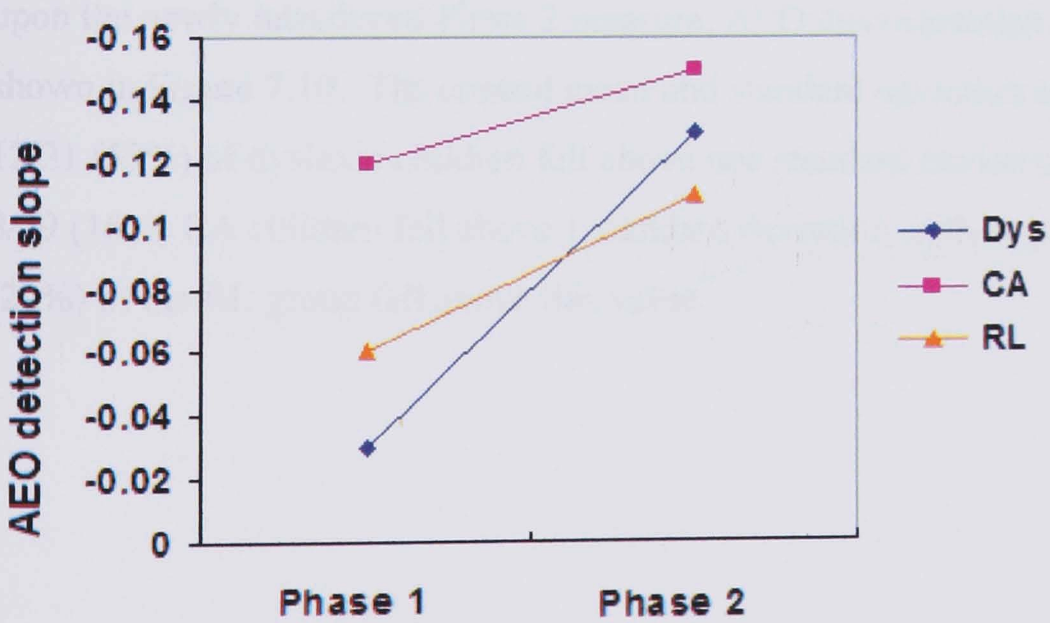
As a comparison to the Phase 1 results, bubble plots showing group psychometric functions for the AEO detection task are shown in Figure 7.8. Graphical representation of the AEO discrimination results in shown in the form of individual scatterplots (see Figure 7.10) and described in more detail in section 7.7.3.

Figure 7.8 Bubble plots of psychometric functions for (a) dyslexic, (b) CA and (c) RL groups - AEO detection task. The size of the bubbles represents the number of trials. Values closer to 1 on the y-axis represent identification judgements of one single modulating sound, with no distinct 'beat'.



In contrast to Phase 1, a one way ANOVA showed no main effect of group with AEO detection as the dependent variable, $F(2,57) = 1.17$, $p = 0.32$. The graph below compares AEO detection performance between groups at Phases 1 and 2. In Phase 2 the performance of all three groups has converged.

Figure 7.9 AEO detection performance at Phases 1 and 2.



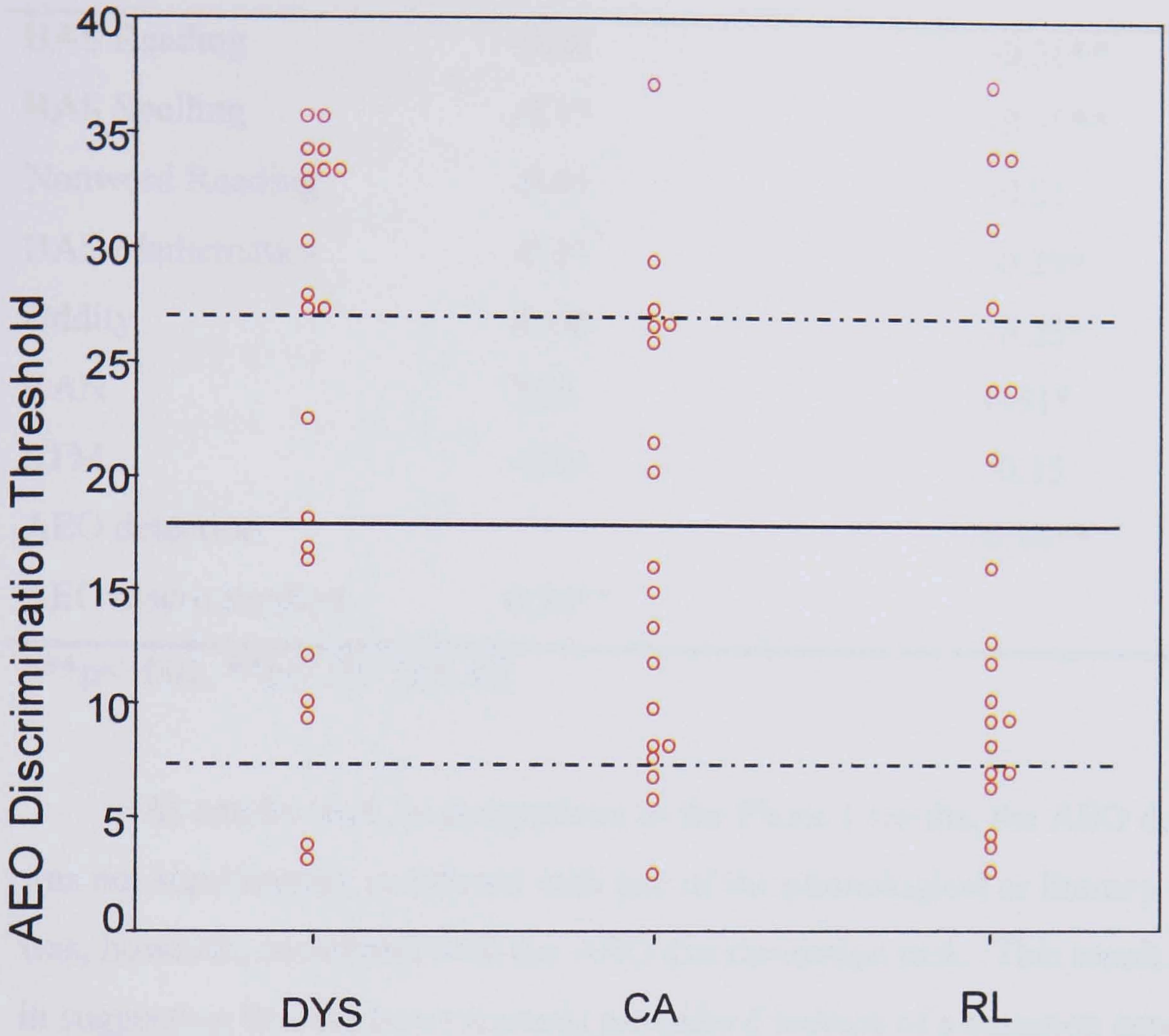
7.7.2 AEO discrimination

For the AEO discrimination task the main effect of group in a one way ANOVA was just approaching significance, $F(2,57) = 2.95$, $p = 0.06$. There was a significant performance difference between the dyslexic children and their CA matched controls, with the dyslexics showing higher discrimination thresholds (i.e. performing more poorly), $F(1,38) = 4.05$, $p < .05$. The thresholds of the dyslexic group were also significantly higher than those of the RL group, $F(1,40) = 4.54$, $p < .05$. There was no significant difference between the CA and RL groups, $F(1,38) = 0.034$, $p = 0.83$.

7.7.3 Individual differences in performance on auditory processing measures

As well as looking at group differences in performance, it is also important to look at individual results. This is especially so in light of the many studies now published that suggest auditory processing difficulties only affect a small subgroup of dyslexic individuals. Indeed, in a meta-analysis of all the recent studies in which individual data was analysed or displayed Ramus (2003) reported that only a total of 67/174 (39%) of dyslexics had observed auditory deficits. It was decided to focus here upon the newly introduced Phase 2 measure, AEO discrimination. A scatter plot is shown in Figure 7.10. The control mean and standard deviation are also marked. 12/21 (57%) of dyslexic children fell above one standard deviation of the CA mean. 3/19 (16%) CA children fell above 1 standard deviation of their group's mean and 5/21 (24%) of the RL group fell above this value.

Figure 7.10 Individual scatter plot of AEO discrimination performance. The bold line indicates the CA mean and the broken lines mark performance at +/- 1 standard deviation respectively.



7.7.4 Concurrent relationships between auditory processing, phonological processing and literacy

In order to explore the relationship between the two AEO measures and phonological processing, reading and spelling, partial correlations controlling for age and WISC IQ were calculated.

Table 7.8 Partial correlations between the basic auditory processing measures and experimental variables controlling for age and IQ

	AEO Detection	AEO Discrimination
BAS Reading	-0.20	-0.36**
BAS Spelling	-0.17	-0.35**
Nonword Reading	-0.05	-0.21
BAS Mathematics	-0.27*	-0.29*
Oddity	-0.08	-0.25*
RAN	0.05	0.31*
STM	-0.14	-0.15
AEO detection		0.34**
AEO discrimination	0.34**	

***p< .001, **p< .01, *p< .05

As can be seen, in comparison to the Phase 1 results, the AEO detection task was not significantly correlated with any of the phonological or literacy measures. It was, however, correlated with the AEO discrimination task. This result is encouraging in suggesting that the two measures are indeed indices of a common aspect of auditory processing. The generally low correlations of the AEO detection task likely reflect the small performance variance seen for this task at Phase 2, which will reduce the task's ability to demonstrate correlatory variance with other skills. The AEO discrimination task showed associations with the reading, spelling, mathematics measures as well as the oddity and RAN phonological measures. There were not correlations with non-word reading or the phonological short-term memory task. Associations had been found between these measures and AEO sensitivity (as measured by AEO detection) in Phase 1, however, in Phase 2 there were clear ceiling effects for the non-word reading task in the CA and RL groups and the lack of neighbourhood density effects for the STM measure at Phase 2 also raised questions about reduced sensitivity for this task. Because of this, in the regression analyses that follow, nonword reading and STM were not used as dependent variables as they had been in Phase 1. As an alternative, another phonological processing measure, paired-associate-learning (PAL) accuracy was entered, as this had proven in chapter 6 to be a measure sensitive to individual differences in phonological skill. A series of four-step fixed entry multiple regression equations were carried out. For each regression, unusual or influential data-points according to the Cook's Distance (Cook's D) metric were examined and no data-points required removal for the regression series reported below[10]. The dependent variables were BAS reading, BAS spelling, phonological awareness (oddity), PAL and RAN. The independent variables were (in a fixed order) (*i*) age, (*ii*) nonverbal IQ, (*iii*) vocabulary, and (*iv*) AEO discrimination. AEO detection was not included in these analyses due to the low correlatory strength observed in Table 7.8. The percentage of variance in the dependent variables explained by the different independent variables is displayed in Table 7.9. Further regression details can be found in Appendix 5.

Table 7.9 Percentage of variance in (a) reading, (b) spelling, (c) phonological awareness (oddity), (e) paired associate learning (PAL) and (f) rapid automatised naming (RAN) explained by the different independent variables in separate fixed entry multiple regression equations. Steps 1 - 4 were always the same (age, nonverbal IQ, vocabulary and AEO discrimination).

	Dependent Variable (Columns show separate equations)				
	(a) Reading	(b) Spelling	(c) Oddity	(d) PAL	(e) RAN
	R^2 change	R^2 change	R^2 change	R^2 change	R^2 change
Step 1: Age	0.00	0.00	0.01	0.00	0.04
Step 2: Blocks	0.04	0.05	0.06	0.11*	0.16***
Step 3: Vocab	0.11**	0.08*	0.07*	0.12**	0.00
Step 4: AEO discrimination	0.12**	0.11**	$0.05^{p=.07}$	0.11**	$0.05^{p=.06}$

***$p< .001$, **$p< .01$, *$p< .05$

Note. DV = Dependent variable

[10] The AEO detection results from the RL outlier also remained out of the regression analyses.

Although not predicting as much variance in the dependent variables as at Phase 1, the AEO measure at Phase 2, AEO discrimination, contributes significantly (11-12%) to the variance in reading, spelling and paired associate learning, with contributions approaching significance for the other two phonological processing measures, oddity and RAN.

7.7.5 Longitudinal relationships between auditory processing, phonological processing and literacy

As well as looking at concurrent predictors, in a longitudinal study it is also of interest to look at the relationships between Phase 1 and 2 measures, in order to see if auditory processing skills at Phase 1 are good indicators of performance later on. In Table 7.10 partial correlations are shown between auditory processing measures in Phase 1 and auditory, phonological and literacy measures in Phase 2. In these correlational analyses age and IQ are partialled out in the top right correlations, whilst age, IQ and reading ability at Phase 1 (BAS) are partialled out in the bottom left set. The latter, more stringent analysis was carried out to control for the autoregressive effects of reading ability on itself, agreed to be an important methodological consideration in any longitudinal study of reading (e.g. Elbro, Borstrom & Peterson, 1998; Castles & Coltheart, 2004).

With age and IQ partialled out, strong correlations were seen between AEO detection at Phase 1 and many of the Phase 2 measures, most significant for reading and spelling. There were also significant correlations with maths and the phonological processing tasks of oddity, PAL and RAN. The relationship between AEO detection at Phase 1 and AEO discrimination at Phase 2 was almost significant, whilst that between AEO detection at Phases 1 and 2 was not at all significant. This is a surprising finding, however, is perhaps explainable by the lack of group differences observed at Phase 2, suggesting this task is much less sensitive at the second administration.

The RFD and TOJ tasks at Phase 1 showed a similar pattern of associations to Phase 2 measures as the AEO detection task, however these relationships were generally weaker.

When reading level at Phase 1 was also partialled out of the correlation calculations, almost all significant relationships disappeared. This likely reflects the obvious intimacy between initial reading level and the other measures administered here. Because of this, however, further regressional analyses were not carried out upon these results.

Table 7.10 Bivariate correlations between basic auditory processing measures and experimental variables (top right). Partial correlations controlling for age, IQ and Phase 1 BAS reading (bottom left). A '1' at the end of a variable name denotes a measure taken at Phase 1, whilst a '2' denotes measures taken at Phase 2.

	Read 1	AEO Det 1	RFD 1	TOJ 1	Read 2	Spell 2	Math 2	Odd 2	PAL 2	RAN 2	AEO Det 2	AEO Disc 2
Read 1		-0.59***	0.40**	-0.27*	0.87***	0.90***	0.61***	0.69***	0.50***	-0.34**	-0.07	-0.32*
AEO Det 1			-0.32**	-0.25*	-0.50***	-0.55***	-0.37**	-0.40**	-0.34**	0.34**	0.01	0.25 (p=.06)
RFD 1		-0.12		0.45***	0.36**	0.40**	0.43**	0.48***	0.44**	-0.22	-0.38**	-0.40**
TOJ 1		0.11	-0.46***		-0.29*	-0.37**	-0.33*	-0.28*	-0.29*	0.30*	0.18	0.40**
Read 2		0.04	0.04	-0.02		0.85***	0.55***	0.63***	0.52***	-0.29*	-0.20	-0.36**
Spell 2		-0.04	0.10	-0.18	0.29*		0.61***	0.66***	0.60***	-0.38**	-0.17	-0.35**
Math 2		-0.02	0.26	-0.17	0.05	0.18		0.49***	0.39**	-0.32*	-0.27*	-0.29*
Odd 2		0.02	0.31*	-0.09	0.06	0.12	0.12		0.43**	-0.21	-0.08	-0.25*
PAL 2		-0.06	0.30*	-0.15	0.19	0.40**	0.12	0.14		-0.37**	-0.38**	-0.38**
RAN 2		0.18	-0.10	0.21	0.00	-.18	-0.16	-0.04	-0.24		0.05	0.31*
AEO Det 2		-0.05	-0.39**	0.17	-0.28*	-0.23	-0.29*	-0.05	-0.40*	0.03		0.34**
AEO Disc 2		0.08	-0.31*	0.33*	-0.18	-0.16	-0.13	-0.06	-0.27*	0.05	0.34**	

***p< .001, **p< .01, *p< .05

Note: Read = BAS Reading, AEO Det = AEO detection task, RFD = Rapid frequency discrimination, TOJ = Temporal Order Judgement, Spell = BAS Spelling, Math = BAS Mathematics, Odd = Oddity task, PAL = Paired Associate Learning, RAN = Rapid Automatised Naming, AEO Disc = AEO discrimination.

7.8 Phase 2 Discussion

In Phase 2 we see significant group differences between the dyslexic children and both control reading groups in their performance on a measure of AEO sensitivity, in this case, AEO discrimination. Group differences on the AEO detection task had disappeared by Phase 2. This change could be due to the fact that the dyslexic and reading level groups had in effect 'caught up' with the CA group. This suggests that whatever auditory-perceptual limitations the less experienced readers possess, in both the typically-developing RL group and the dyslexic group, positive developmental change occurs in the later primary school years. From the results presented here it is impossible to say whether the improved performance represents similar developmental change in both groups, or whether dyslexic children were able to employ alternative strategies to achieve the same endpoint as the CA and RL controls. This question is one addressed further in the next chapter, when the neurophysiological responses of the three reading groups are examined in relation to amplitude envelope onsets.

Although clear group differences were observed, overlap between all three groups was evident across tasks through the means and standard deviations yielded. The individual scatterplot of AEO discrimination performance at Phase 2 also confirms this observation. Strong associations were also seen between AEO sensitivity and concurrent phonological and literacy ability across groups. Together these findings suggest that AEO sensitivity is important to reading acquisition and reduced AEO sensitivity, perhaps in the context of additional influencing factors, may place limits on the reading trajectory possible. Additional factors could be intrinsic to the child, such as auditory processing deficits for other acoustic cues (e.g. frequency discrimination – an independent weakness or perhaps one consequent upon larger grain-size auditory limitations), or environmental factors, for example reading instruction received.

The dynamic nature of children's literacy learning trajectories highlights the amount of research still needed to understand the path to reading competence. For whilst relative insensitivity to AEO salience has been found in the dyslexic group here, if a central claim of the AEO sensitivity hypothesis is that this auditory factor is important because of its crucial role in word segmentation from earliest infancy, then AEO sensitivity must be measured in much younger infants through prospective studies that can follow the language and literacy trajectories of the same individuals over time. Although psychoacoustic testing in young infants can become fraught with concerns over measurement reliability, methods such as Event-Related-Potential (ERP) measurement, described in the next chapter, offer exciting new possibilities in terms of overcoming some of these issues.

Chapter 8 – Neurophysiological investigation of amplitude envelope sensitivity in dyslexia

8.1 Introduction

In the previous chapter evidence was presented which suggested a strong association between school-aged children's amplitude envelope onset (AEO) sensitivity and their literacy ability. As discussed in chapter 4, this is by no means the first study to find associations between an auditory processing skill and literacy ability, but what has not yet been convincingly demonstrated is a *causal* relationship between the two. The hypothesis put forward here is that AEO sensitivity is causally important through the perceptual cues it provides at the level of syllables, which then allows well-specified phonological representations to be established. Because dyslexia is a developmental difficulty, a further assumption of the hypothesis is that this insensitivity may be present from early in development. In order to test this hypothesis, we need to know about infant auditory perception, to see if there is a specific insensitivity to AEO variation. Given the caveats observed in auditory psychoacoustic testing, even of older children, researchers have sought new ways to assess auditory processing in children. One potential solution is the use of neurophysiological assessment techniques. By using sensors placed on an individual's scalp, superficial cortical activity in response to auditory stimuli can be recorded and group differences explored. This technique requires no active co-operation from the participant and so is useful for infant studies. It also has the potential to inform us in much greater depth as to the level of conscious processing occurring, as well as the time course and distribution of cortical responding. This chapter describes a preliminary study to look at cortical responses to AEOs within dyslexic and typically-developing children. It was of interest to confirm the presence or absence of neural processing differences to AEOs between the groups at school age, as well as to begin exploring the nature of these differences. The chapter begins by reviewing current knowledge concerning neurophysiological responses to AEO variation, so far only studied in healthy adults.

8.1.1 Previous ERP studies of AEO rise time processing

In chapters 4 and 7 rise time has been identified as an important variable determining the salience of amplitude envelope onsets. A handful of studies have examined neurophysiological responses to rise time variation within tone burst stimuli and in healthy adult volunteers. These studies were largely carried out by audiologists interested in the role of different acoustic variables in perception. Although different terminology has been used, when referring to N1, this is the fronto-central N1b component, most prominent in adults. As with behavioural studies wanting to vary a specific auditory variable in a controlled manner, all the studies reported here have looked at rise time variation within non-speech, as opposed to speech stimuli.

The first notable study was that of Onishi and Davis (1968) who reported that whilst changes in N1 response amplitude to AEO rise times below 30ms were small, between 30ms and 300ms N1 amplitude decreases and latency increases were evident, especially between 30 and 50ms. Subsequent studies (Lamb & Graham, 1967; Skinner & Jones, 1968; Ruhm & Jansen, 1969; Loveless & Brunia, 1990) confirmed these basic findings and although there was not complete consensus on the presence of significant N1 change with rise times longer than 100ms, divergence of results was attributed to procedural differences such as overall intensity levels and whether or not individual detection thresholds were taken into consideration.

A further study by Kodera, Hink, Yamada and Suzuki (1979) compared brain stem auditory evoked responses, middle latency responses and longer latency N1 responses to tone stimuli differing in AEO rise time. The authors reported equivalent N1 responses to the studies above, but also qualitatively similar responses across all these neural processing levels. From this Kodera et al. concluded that rise time augmentation precipitates delayed and less synchronous neural discharge from the level of the cochlea upwards.

Finally, Lyytinen, Blomberg and Näätänen (1992) carried out a study which included MMN responses to tone rise time change, specifically short rise time deviants (2ms) presented in the context of longer rise time standards (24ms). MMN difference waves were observed for this stimulus contrast.

8.1.2 Limitations of previous ERP studies of AEO rise time processing

Although these early findings have not been disputed, they were almost exclusively carried out when ERP recording and analysis techniques were much less advanced than those available now. The results therefore generally rely on findings from a handful of electrodes and a relatively small number of trials. In the light of this fact, a pilot study was run as part of the current thesis to confirm the presence and nature of ERP responses to AEO rise time variation. This pilot study is described in Appendix 6 and was run with a group of healthy adult volunteers. To summarise the findings, in Experiment 1, N1b amplitude differences were clearly detected for tone stimuli with rise times of 15 and 185ms respectively. The N1 responses were bilaterally distributed. A further experiment confirmed that these responses were not due to differences in overall stimulus intensity, but could be attributed more specifically to rise time differences.

8.1.3 Summary and research goals

To summarise what we know about neural responses to stimuli differing in AEO rise time, we know that most obviously at the cortex, shorter, more abrupt AEOs elicit a greater and perhaps faster synchronised neuronal response than longer AEOs. This is indexed in adults by greater amplitude and reduced latency of N1 responses recorded front-centrally. We also know that information concerning AEO rise time variation is fed forward to higher levels of auditory encoding, as indexed by the elicitation of MMN responses when AEO rise times change from the expected length.

The primary goal of the experiment reported here was to characterise the neural correlate of the behavioural insensitivity to AEO rise times observed in dyslexic children. Thinking back to chapter 4, although the AMFR findings of Menell, McAnally and Stein (McAnally and Stein, 1997; Menell & McAnally, 1999) are the most relevant to the current study, given the weak signal:noise ratio of the AMFR component, it was felt that this was not the optimal response to measure within a young sample population. Because almost all our knowledge concerning ERP responses to AEO variation is derived from N1 studies, and because of the N1's known importance in onset detection (Näätänen & Winkler, 1999) this component was the focus here. The N1 is also a logical starting point given its status as the first easily identifiable index of cortical stimuli- specific sensory encoding.

The key research questions were:-

1. Will typically-developing children show the same patterns of N1 response to AEO rise time variation as adults i.e. reduced N1 amplitude with rise time augmentation?

2. Will we find group differences in N1 responses to AEO rise time variation between the dyslexic children and their age-matched peers?

3. If group differences are present, what is their nature?

4. How do the N1 responses across groups correlate with behavioural auditory processing, phonological and literacy measures?

8.2 Method

8.2.1 Participants

Children who had taken part in the previous investigations of this thesis were the ideal participants for the ERP study, due to the rich amount of information already gathered concerning their literacy, phonological and auditory processing skills. Because, however, the ERP recording procedure entailed children and families travelling to the Institute of Child Health, London, as opposed to seeing children at their schools or homes, the participation rate for this study was lower than previously. Recordings were carried out for 6 dyslexic children (one of whom was not in the other studies of this thesis but of appropriate age and ability), 4 chronological age matched children and 6 reading level matched children. The data from one reading level matched child could not be used due to an excessively noisy signal. The ERP recordings were administered at the end of Phase 2 of the behavioural testing and so the subgroup characteristics, taken from the Phase 2 assessment battery are shown in Table 8.1.

Table 8.1 Participant characteristics for Dyslexic readers, Reading Level Controls (RL) and Chronological Age (CA) controls participating in the ERP study

	Dyslexic	CA	RL
N	6	4	5
Age in years and months	10;5 (11m)	10;3 (6m)	9;10 (4m)
Reading Ability Score	118.00 (21.34)	186.50 (4.12)	150.40 (17.34)
Spelling Ability Score	82.83 (7.22)	148.00 (5.03)	104.00 (17.54)
IQ	109.50 (12.82)	121.50 (3.87)	112.80 (11.08)
AEO Discrimination Threshold	30.89 (7.19)	16.12 (10.01)	15.40 (12.86)

Note. Standard deviations are shown in parentheses

From visual inspection of Table 8.1 there are several important points to note. Firstly, as relatively old RL children volunteered for the ERP experiment, the chronological age differences between the dyslexic, CA *and* RL groups are small. Due to the small Ns, these differences were analysed through a series of non-parametric Kruskal Wallis tests. No significant differences were present in between any of the groups and their chronological age in months, $\chi^2 = 1.51$, $p = 0.47$. There were significant overall group differences in reading and spelling (reading $\chi^2 = 10.28$, $p<.01$; spelling $\chi^2 = 10.56$, $p<.01$). The CA group had significantly higher reading and spelling scores than the RL group (reading χ^2 = 5.55, p<.05; spelling χ^2 = 6.05, p<.05) whilst the RL group had significantly higher reading spelling scores than the dyslexic group (reading χ^2 = 4.07, p<.05; spelling χ^2 = 4.11, p<.05) Differences in IQ scores across groups were not significant, χ^2 =2.62, p = 0.27.

After careful consideration it was determined that a merging of the two control groups would be the most informative way to analyse the subsequent data. By doing this, the group averages would be more robust (a control group of 9 children instead of groups of 4 & 5) and the result would be two groups matched for age and IQ, though differing significantly in reading and spelling scores. The characteristics of the new group compositions are confirmed in Table 8.2. Additional performance means for phonological processing tasks administered in Phase 2 and used in correlational analyses later in this chapter are also included. The combined control group will henceforth be referred to as the com-control group.

Mann-Whitney U tests confirmed no significant differences between groups in age (U = 21.00, z = -0.71, p = 0.53) and IQ (U = 17.50, z = -1.12, p = 0.27), with significant differences present in reading (U = 4.00, z = -2.27, p = 0.005), spelling (U = 4.00, z = -2.72, p = 0.005) and AEO discrimination threshold (U = 8.00, z = -2.24, p = 0.03). Further significant differences are signalled by asterisks in Table 8.2.

Table 8.2 Participant characteristics for Dyslexic readers and the Com-control group participating in the ERP study

	Dyslexic	Com-control
N	6	9
Age in years and months	10;5 (11m)	10;0 (5m)
Reading Ability Score	118.00 (21.34)	166.44** (22.78)
Spelling Ability Score	82.83 (7.22)	123.56** (26.48)
IQ	109.50 (12.82)	116.67 (9.38)
AEO Discrimination Threshold	30.89 (7.19)	15.72* (10.97)
Oddity % Correct	58.00 (9.10)	78.90** (13.65)
Paired Associate Learning % Correct	42.20 (18.27)	77.44** (12.43)
RAN (time in seconds)	65.60 (10.24)	57.56 (5.53)

Note. Standard deviations are shown in parentheses
***p<.0001, **p<.01, *p<.05

The two figures overleaf highlight the performance of the children participating in the ERP experiment in relation to the larger longitudinal group. Displayed are reading performance and AEO discrimination at Phase 2.

Figure 8.1 ERP experiment participants' (highlighted in green) reading ability in relation to larger longitudinal group. The blue circle is an additional dyslexic child who participated in the ERP expt.

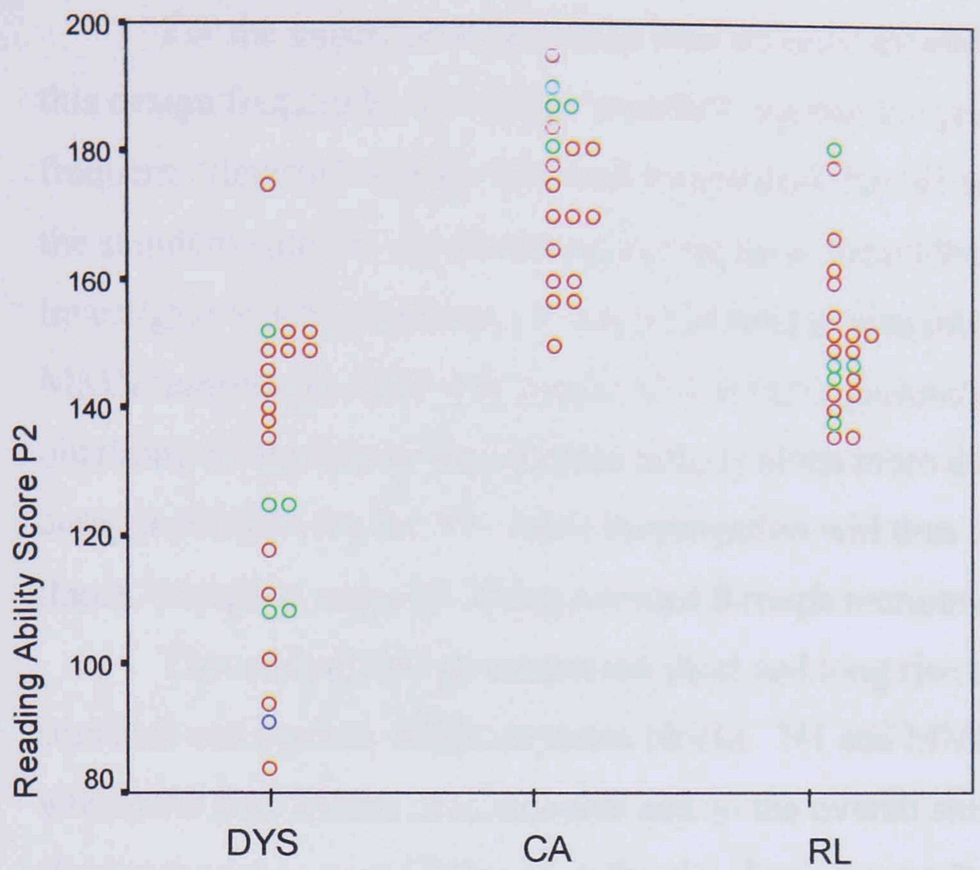
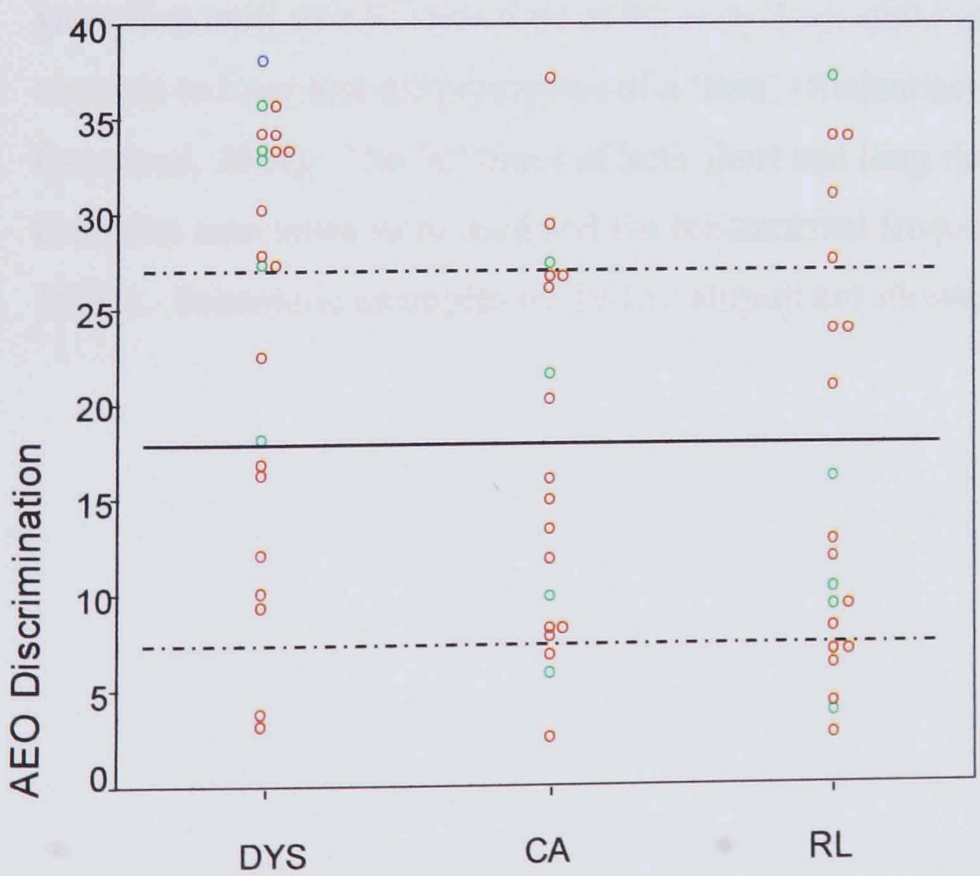


Figure 8.2 ERP experiment participants' (highlighted in green) AEO discrimination thresholds in relation to larger longitudinal group. The blue circle is an additional dyslexic child who participated in the ERP expt. The bold line indicates the CA mean (n=19) and the broken lines mark performance at +/- 1 standard deviation respectively.



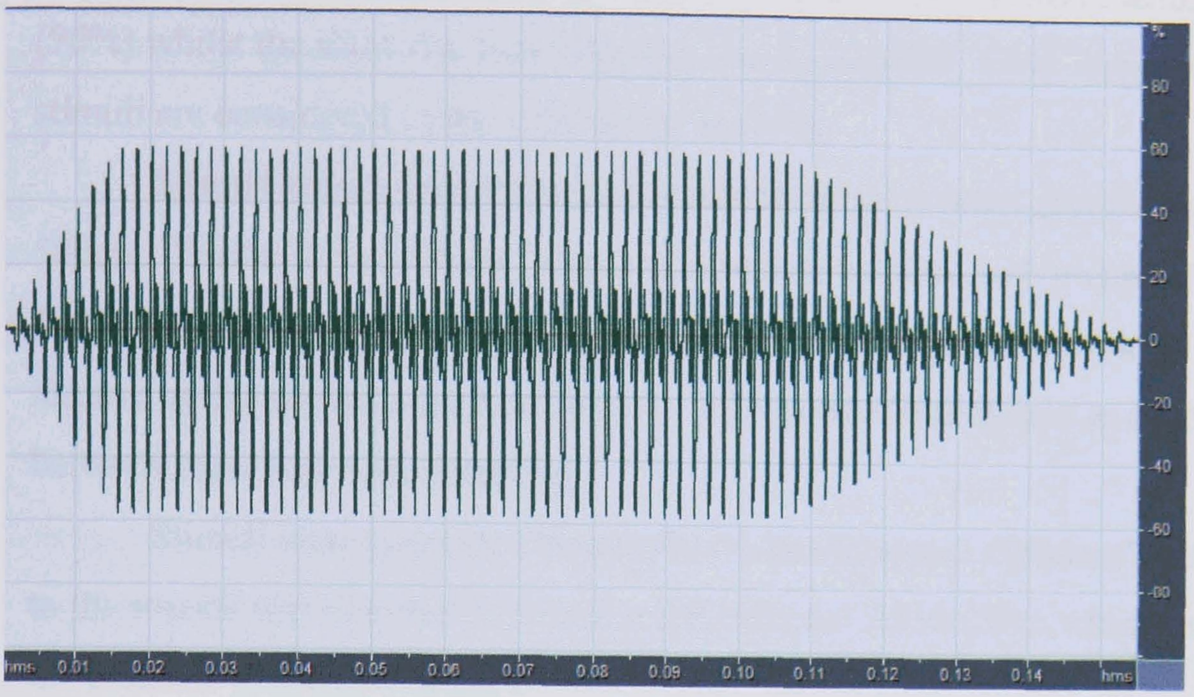
8.2.2 Experimental design

For the experiment described here an auditory oddball design was used. Within this design frequently occurring, 'standard' stimuli are presented alongside less frequent, 'deviant' stimuli; it is well-established that N1 responses can be elicited by the standard stimuli. As discussed in chapter 4, the oddball design can also be used to investigate MMN responses. It was of interest to also investigate the nature of the MMN response to AEO rise change within the experimental groups here, however obtaining a satisfactory signal:noise ratio is much more difficult for the MMN component than for the N1. Such investigation will thus not be reported in the present thesis, though is currently being pursued through recruitment of a larger sample group.

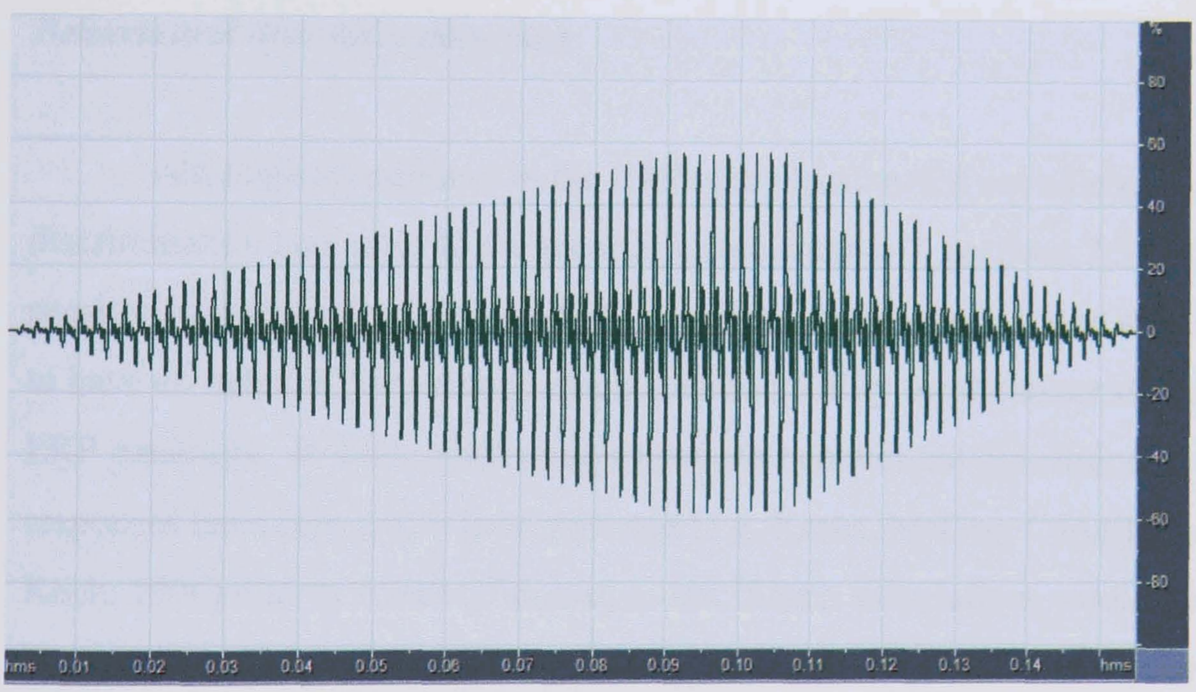
The oddball design contrasted short and long rise time stimuli, both acting as standard and deviant within separate blocks. N1 and MMN components both occur within the first 250ms post-stimulus and so the overall stimuli duration had to be much shorter than those used behaviourally (the shortest overall stimulus length used, in the Phase 2 AEO discrimination, was 3570ms, i.e. almost 4 seconds). Stimulus duration was set at 155ms. Within this time, the 'short' rise time stimuli had a rise time of 15ms and the 'long' rise time stimuli a rise time of 90ms. We know from recent behavioural work that with an AEO rise time of 90ms dyslexic children are more likely than their controls to have lost the perception of a 'beat' (Richardson, Thomson, Scott & Goswami, 2004). The fall times of both short and long rise time stimuli were 50ms. Complex sine tones were used and the fundamental frequency of the stimuli was 500Hz. Schematic examples of the two stimuli are shown in Figure 8.3.

Figure 8.3 Schematic examples of an a) 15ms and b) 90ms onset rise time stimulus. Time is shown on the horizontal axes in minutes. Amplitude is shown on the vertical axes in %.

a) 15ms rise time



b) 90ms rise time



8.2.3 Experimental tasks and procedure

Stimuli were presented within the oddball paradigm described above. The experimental design consisted of two blocks of stimuli, each repeated twice and in a counterbalanced order across children. One block contained 1000 stimuli, thus 4000 stimuli were presented in total. Each block lasted just over 8 minutes with an interval of at least 2 minutes separating them. In Block A, the short rise time stimulus was presented as the standard stimulus with a probability of 90%. Long rise time stimuli were presented as deviants. In Block B the long rise time stimulus acted as the standard (90%) whilst the short rise time stimulus was the deviant. Only responses to standard stimuli are considered in the subsequent analysis.

Stimuli were presented with a constant stimulus onset asynchrony (SOA) of 500ms. Whilst N1 amplitude is known to reduce as SOA is shortened (Näätänen, 1987), shorter SOAs allow more stimuli to be presented as a function of recording time, improving the overall signal:noise ratio. 500ms was thus chosen as a 'middle ground' between these two considerations.

Stimuli were presented binaurally via headphones. Children's active attention to the sounds was diverted by use of a self-selected silent video which they watched for the duration of the recording.

Behavioural discrimination task

Although all children in the ERP study had carried out a behavioural AEO discrimination task prior to the recording (see chapter 7, sections 7.5-7.8) in which sensitivity to stimuli varying in AEO rise time was assessed, it was also felt important to have an index of behavioural discrimination ability for the exact stimuli used in the ERP paradigm. Robust relationships between behavioural discrimination and ERP responses have previously been reported (e.g. Kraus, McGee, Carrell, Zecker, Nicol & Koch, 1996) and so it was of interest to see if such associations would be replicated here, and how both these measures would associate with the wider battery of auditory, phonological and literacy measures the children had carried out. Immediately before the ERP recording each child was presented with an active same-different judgement task. The children heard pairs of sounds in four possible combinations – long rise time ('RT')/long RT, short RT/short RT, long RT/short RT, short RT/long RT. The children were asked to decide whether the two sounds were the same or different and responded by pressing a corresponding mouse button. There were six practice trials followed by 32 experimental trials and the commencement of each new trial was self-paced by the participant. The stimulus onset asynchrony (SOA) between sounds within a pair was 500ms.

ERP recording and data processing

Stimuli were presented using Presentation 0.55 (Neurobehavioral Systems Inc.) software, with event codes simultaneously sent to the ERP recording system. Recordings were carried out via a SynAmps amplifier with system band pass 0.15-70Hz, 50Hz notch filter and a digital sampling rate of 250Hz. The resultant continuous EEG was acquired with NeuroScan 4.2 software programme and saved for later analysis. During the recording children were seated in a comfortable chair whilst watching a self-selected silent video. Twenty one Ag/AgCl recording electrodes were used and these were fitted to an Easy-Cap. Electrode sites were prepared with alcohol and NuPrep to reduce scalp impedances. Lectron II conductivity gel was also applied to each cap-electrode fitting point. Recordings were referenced to the nose and a ground electrode was located on the forehead. Vertical eye movements were recorded via two electrodes placed above the right eye and below the right outer canthus respectively (electro-oculogram, henceforth 'vEOG'). Electrodes were placed according to the International 10-20 system at the scalp sites of Fp1, FP2, Fz, F3, F4, F7, F8, Cz, C3, C4, T1, T2, T3, T4, T5, T6, Pz, P3, P4, LM & RM.

Data was filtered off-line with a low pass 25Hz filter. For children whose data contained excessive amounts of eye-blink artefacts the Neuroscan blink reduction regression algorithm was used. At least 40 blink artefacts of greater than 10% deviation were selected as templates from the continuous EEG file and entered into the computation. The continuous EEG was then split into 600ms epochs with a 100ms pre-stimulus baseline. Baseline correction was carried out to the average pre-stimulus amplitude. Epochs containing amplitudes greater than +/- 100 μV were subsequently rejected. Average waveforms were then computed for each stimulus type.

ERP data presentation

The following conventions are used in the presentation of ERP data. Electrode locations refer to the International 10-20 system. Units are microvolts (for peak amplitudes) and milliseconds (for peak latencies). As is a common convention in ERP reporting, the scale on waveform figures shows increasing negativity as the y-axis goes upwards.

8.3 Results

8.3.1 Behavioural same-different task

The results from this task were calculated as "hit rate" scores. Hit rate is defined as the % correct detection of "different" trials, minus % false alarms ("same" trials classified as "different"). Hit rates for the dyslexic and control groups are given in Table 8.3.

Table 8.3 Mean hit rates for the behavioural rise time same-different judgement task

	Dyslexic	Com-control
Hit rate	52.43 (40.20)	58.76 (38.82)

Note. Standard deviations in parentheses

As can be seen from Table 8.3 both groups found this task difficult, although in both cases groups performances were significantly above chance (chance hit rate being 0% - equal probability of correctly detecting a difference and falsely ascribing difference to a same pair, Dys, $t(5) = 3.19$, $p<.05$; com-control, $t(8) = 4.54$, $p<.01$). A Mann Whitney U test confirmed that there were no significant group differences on this task ($U = 24.00$, $z = -0.354$, $p = 0.77$). This contrasts with the groups' AEO discrimination performance, in which clear group differences were present ($U = 8.00$, z

= -2.24, p = 0.03). This apparent discrepancy may reflect the very different nature and sensitivity of the two tasks, with the same-different judgement task just employing one contrastive rise time difference (15ms vs. 90ms) and the AEO discrimination adaptively presenting a much greater range.

8.3.2 N1 responses

Preliminary investigations

Before examining the 'grand average' waveforms for the N1 responses of the respective reading groups, it was first important to ensure that there were no significant differences between the groups in the number of accepted epochs. The means and standard deviations for the number of accepted epochs between groups are shown in Table 8.4. Mann Whitney U tests confirmed that there were no significant differences between the groups in the number of epochs accepted for analysis. A Wilcoxon Ranked Sign test was also carried out to ensure no significant differences between the number of epochs accepted for the 15ms standard condition as opposed to the 90ms standard condition across groups. There was a mean of 959.13 (SD 299.04) 15ms standard epochs and a mean of 957.27 (SD 288.67) 90ms standard epochs; no significant difference existed between these means, z = -0.17, p = 0.87.

Table 8.4 Accepted epochs for N1 analyses

	Dyslexic	Com-control	Mann-Whitney U	Probability
15ms	1085.83 (283.72)	874.67 (293.45)	U = 17.00 z = -1.18	0.27
90ms	860.33 (234.81)	1021.89 (315.63)	U = 17.00 z = -1.18	0.27

Note. Standard deviation in parentheses

It was also deemed important to confirm the stability of individual N1 responses. This was achieved by split-half averaging. For each child, separate averages were computed for odd versus even epoch numbers, for both the 15ms and 90ms rise time stimuli. N1 latency and peak amplitude were then recorded at a pair of temporal lobe electrode sites showing a high overall degree of voltage change, the left and right mastoids (LM and RM respectively). The similarity of the odd and even epoch averages across groups was then tested statistically using Spearman's rho correlations. A summary of the mean amplitudes, latencies and statistical tests is given in Table 8.5. The correlations between odd and even averages were high across electrode sites, suggesting good stability of individual N1 responses.

Table 8.5 N1 stability

Electrode	Rise Time		Even	Odd	Spearman's rho
LM	15ms	Amplitude	-2.20 (0.88)	-1.81 (1.25)	0.54*
		Latency	107.47 (9.90)	110.13 (15.18)	0.83***
	90ms	Amplitude	-2.07 (1.23)	-1.84 (1.32)	0.76***
		Latency	117.04 (15.09)	120.00 (13.35)	0.48
RM	15ms	Amplitude	-2.20 (1.07)	-1.89 (1.02)	0.59*
		Latency	108.27 (10.19)	109.33 (13.911)	0.78***
	90ms	Amplitude	-2.01 (1.40)	-2.01 (1.45)	0.75***
		Latency	118.00 (17.10)	115.20 (13.20)	0.75***

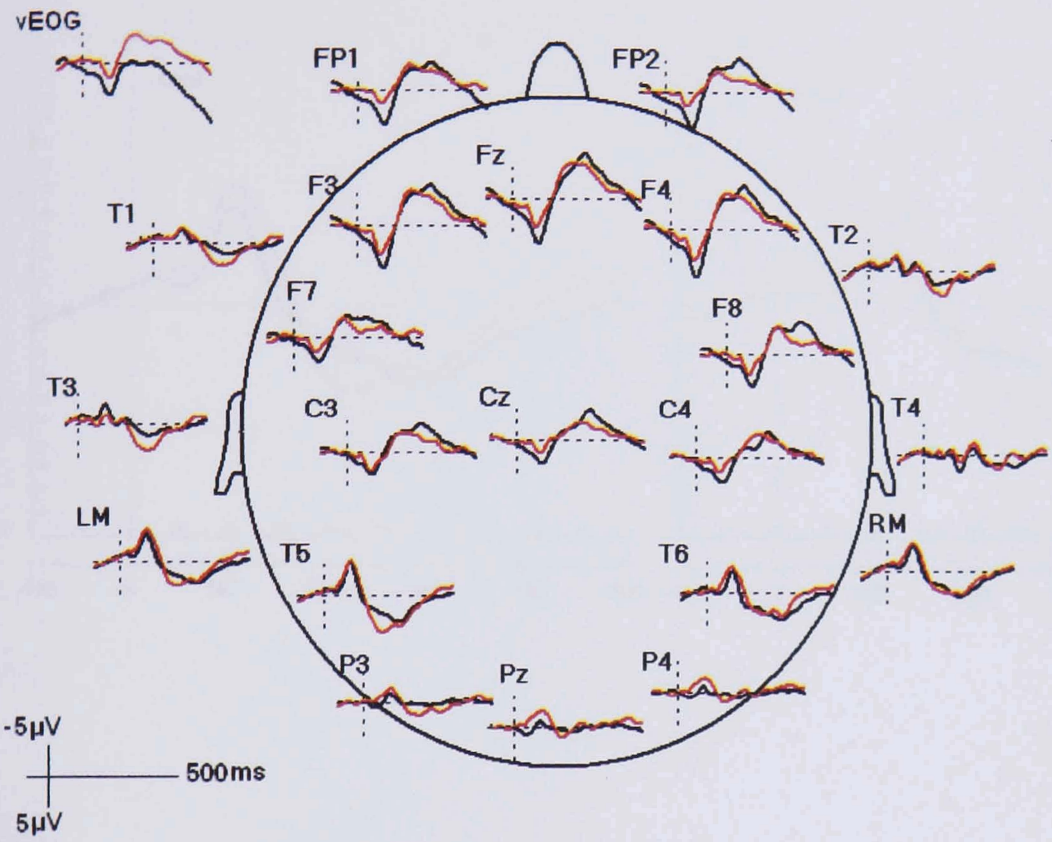
Note. Standard deviations are in parentheses
***p< .001, **p< .01, *p< .05

Having ascertained the reliability of the N1 responses across groups, grand average waveforms were computed for the dyslexic and com-control group for the 15ms rise time and 90ms rise time standard stimuli. Headplots for these grand averages are shown in Figure 8.4. In view of what we know about N1 maturation before adolescence, i.e. the temporal N1a subcomponent is more stable than the fronto-central N1b, the electrodes in the temporal regions were of particular interest (T1, T2, T3, T4, T5, T6, LM & RM). Individual plots for the LM, RM, T5 and T6 electrodes are shown in Figures 8.5, the temporal electrodes of maximal signal.

Figure 8.4 Grand average headplots for a) 15ms and b) 90ms rise time stimuli.

KEY: Dyslexic Com-control

a) 15ms rise time



b) 90ms rise time

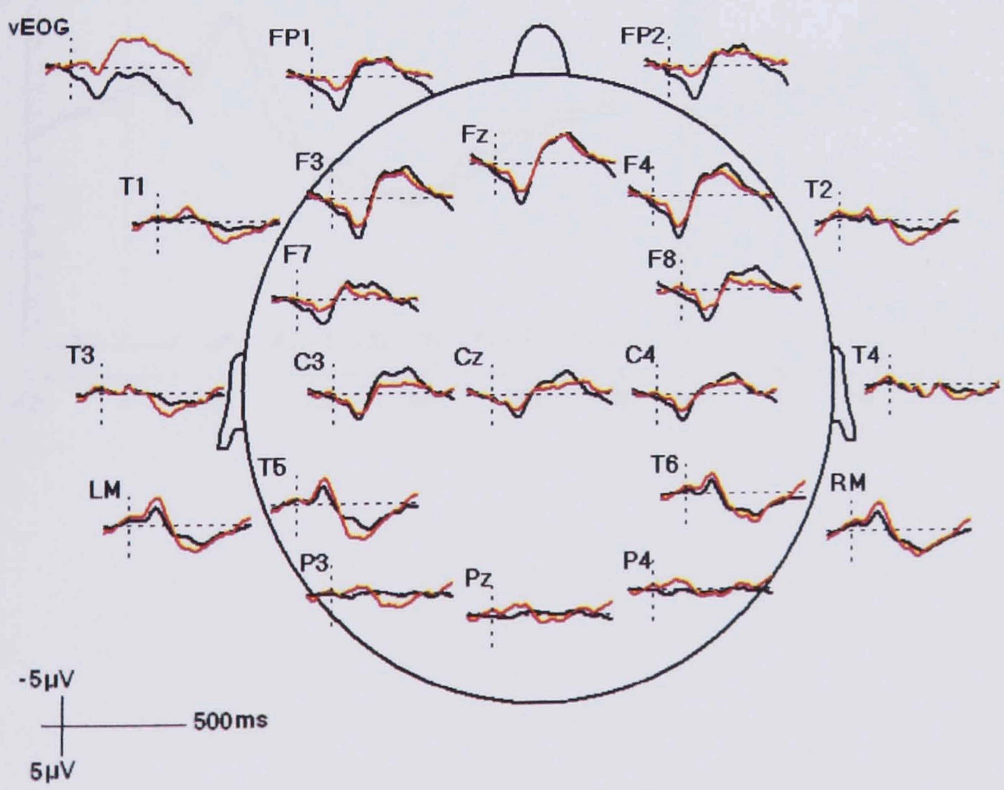
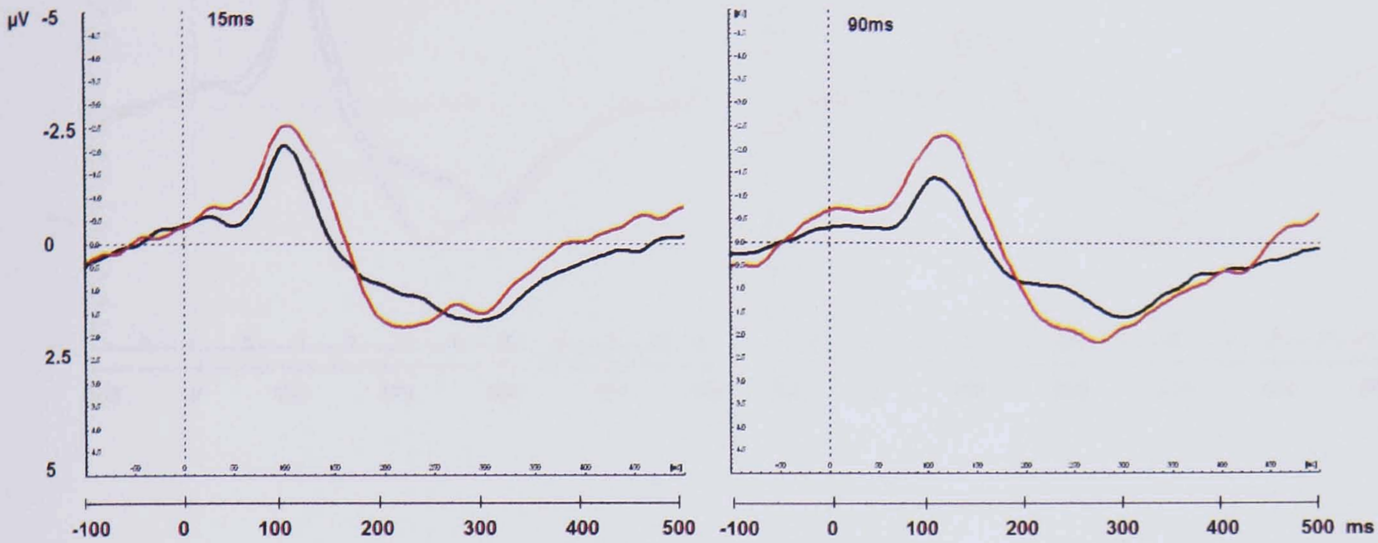


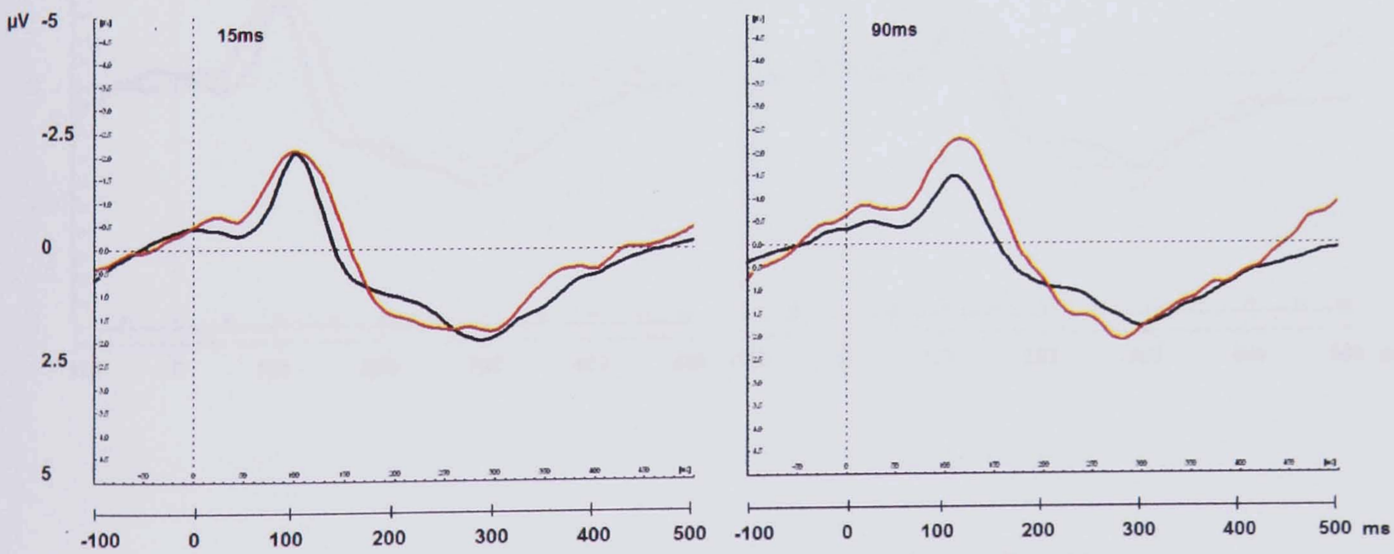
Figure 8.5 Grand average waveforms for 15ms and 90ms rise time stimuli.

KEY: Dyslexic Com-control

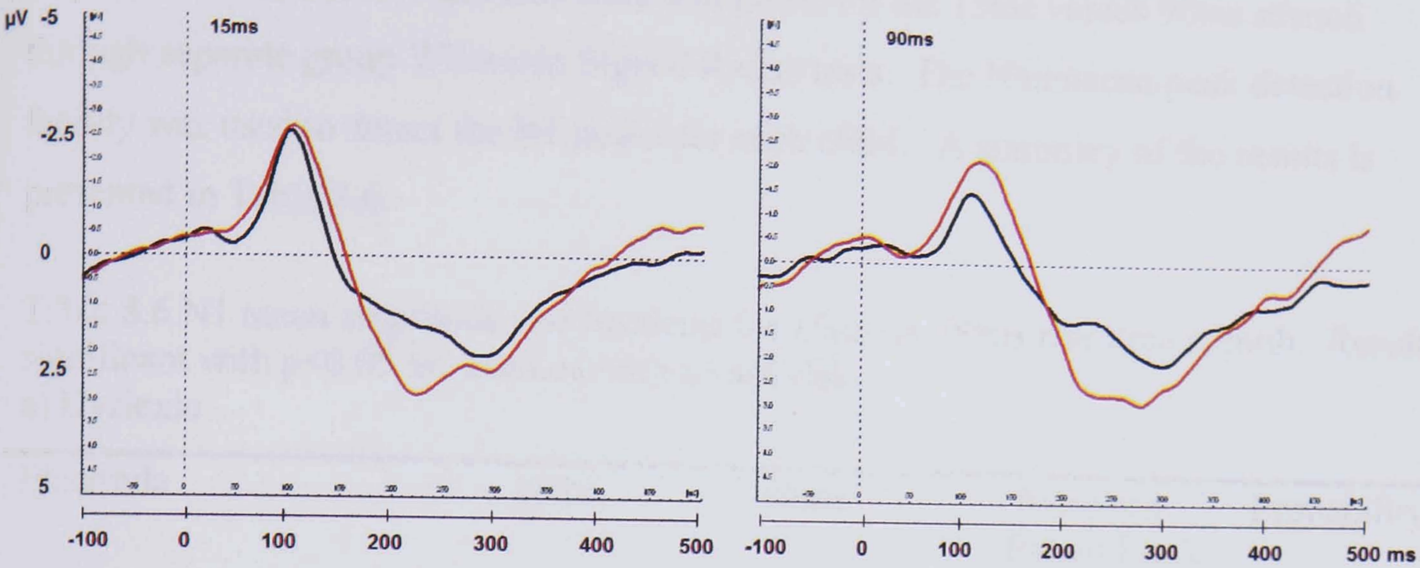
a) LM



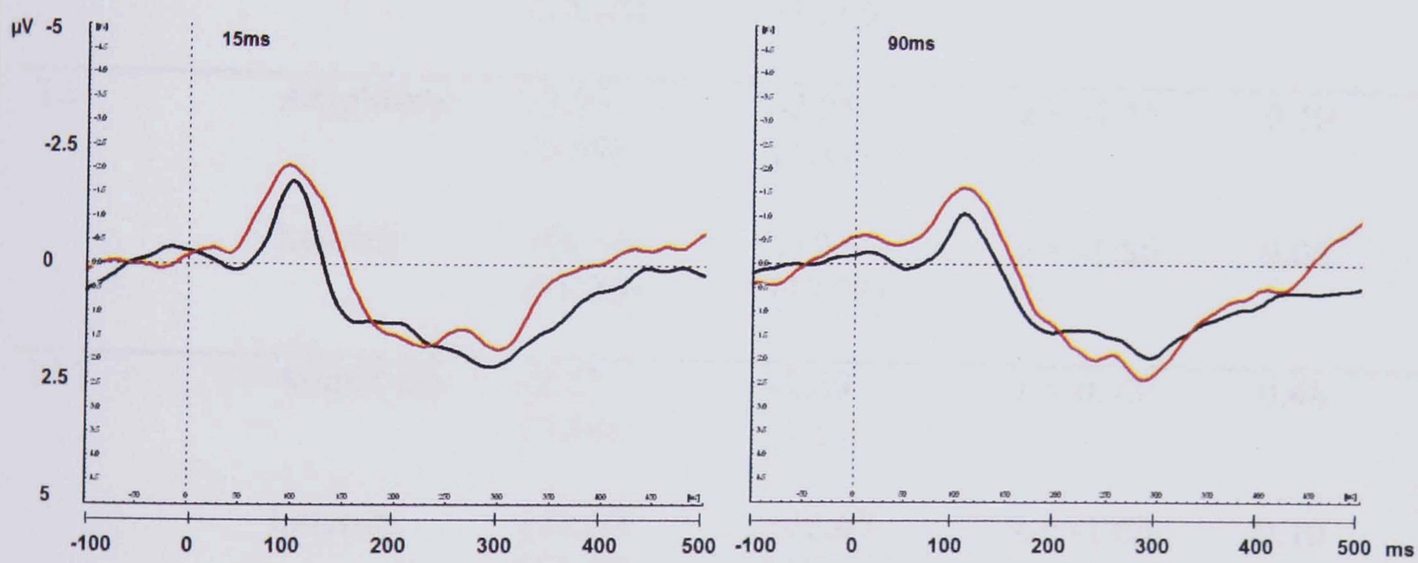
b) RM



c) T5



d) T6



Differences in N1 response to 15ms versus 90ms rise time stimuli

An important aim of this experiment had been to determine whether the preferential N1 responses to shorter rise times seen in adults (indexed through an increased N1b amplitude) would also be observed in a child sample. Although we have been focusing here upon the temporal N1a, one would expect this to behave similarly to the N1b, yielding increased amplitudes for shorter as compared to longer rise times. In order to confirm this differential response statistically, N1a amplitude and latency responses at T5, T6, LM and RM were compared for the 15ms versus 90ms stimuli through separate group Wilcoxon Signed Ranks tests. The Neuroscan peak detection facility was used to detect the N1 peaks for each child. A summary of the results is presented in Table 8.6.

Table 8.6 N1 mean amplitude and latencies for 15ms vs. 90ms rise time stimuli. Results significant with $p<0.05$ are marked with an asterisk.
a) Dyslexic

Electrode		15ms	90ms	Wilcoxon Paired Rank Test	Probability
T5	Amplitude	-3.04 (1.16)	-2.42 (1.22)	z = -0.73	0.46
	Latency	112.67 (14.18)	120.67 (13.00)	z = -1.51	0.25
T6	Amplitude	-2.54 (0.99)	-2.05 (1.37)	z = -1.15	0.10
	Latency	106.67 (18.36)	110.67 (17.28)	z = -1.86	0.06
LM	Amplitude	-2.75 (0.64)	-2.49 (1.14)	z =-0.73	0.46
	Latency	111.33 (13.49)	116.67 (10.56)	z = -1.63	0.10
RM	Amplitude	-2.43 (0.80)	-2.61 (1.74)	z = -0.31	0.75
	Latency	107.33 (16.28)	114.67 (14.90)	z = -1.63	0.10

b) Com-control

Electrode		15ms	90ms	Wilcoxon Paired Rank Test	Probability
T5	Amplitude	-2.04 (0.93)	-1.42 (0.93)	z = -1.96	0.05*
	Latency	105.78 (10.02)	123.11 (26.67)	z = -2.04	0.04*
T6	Amplitude	-1.43 (1.30)	-0.97 (0.84)	z = -1.60	0.11
	Latency	105.78 (9.40)	112.89 (24.88)	z = -1.61	0.11
LM	Amplitude	-1.69 (0.85)	-1.20 (0.66)	z = -2.43	0.02*
	Latency	104.89 (7.94)	119.56 (15.03)	z = -2.23	0.03*
RM	Amplitude	-1.81 (1.01)	-1.35 (0.51)	z = -2.19	0.03*
	Latency	104.89 (5.93)	115.56 (13.03)	z = -2.40	0.02*

Note. Standard deviation in parentheses

Within the dyslexic group there are no significant differences in either amplitude or latency for the N1 responses to 15ms versus 90ms rise time stimuli. In contrast, at three out of four of the temporal electrode sites focused upon here, the com-control group demonstrate significant differences in both the amplitude and latency of their N1 responses to the contrasting rise time stimuli.

Differences in N1 response: groups effects

Visual inspection of Figure 8.5 shows that for the 15ms rise time stimuli the dyslexic and com-control groups exhibit little difference in their responses at the 50ms – 150ms time window of the N1 peak. However for the 90ms rise time stimuli, whilst the com-control group show the expected reduction in peak amplitude for the slower rise time compared to the 15ms rise time stimuli, the dyslexic group do not show an effect of stimulus type. To confirm these group differences statistically Mann-Whitney U tests were carried out at the electrode sites of maximal signal: T5, T6, LM and RM. Group mean peak amplitudes and latencies for these electrode sites, for the 15ms and 90ms rise time stimuli are shown in Table 8.7.

The Mann-Whitney U tests found a significant group difference between the LM amplitudes for the 90ms stimuli, with the dyslexic group exhibiting greater peak amplitudes than the control group. One further amplitude difference at 15ms (T6) and all three of the other 90ms amplitude differences were approaching significance in the same direction. No group differences at or approaching significance were seen within the N1 latency measures.

Table 8.7 Summary of group differences in N1 mean amplitude and latencies. Results significant with $p<0.05$ are marked with an asterisk.
a) 15ms rise time

Electrode		Mann-Whitney U	Probability
T5	Amplitude	U = 14.00 z = -1.53	0.15
	Latency	U = 22.00 z = -0.59	0.61
T6	Amplitude	U = 12.00 z = -1.77	0.09
	Latency	U = 23.00 z = -0.48	0.69
LM	Amplitude	U = 10.00 z = -2.00	0.05
	Latency	U = 19.50 z = -0.90	0.39
RM	Amplitude	U = 21.00 z = -0.71	0.53
	Latency	U = 22.50 z = -0.53	0.61

b) 90ms rise time

Electrode		Mann-Whitney U	Probability
T5	Amplitude	U = 11.00 z = -1.89	0.07
	Latency	U = 25.50 z = -0.18	0.86
T6	Amplitude	U = 11.00 z = -1.89	0.07
	Latency	U = 22.00 z = -0.59	0.61
LM	Amplitude	U = 7.00 z = -2.36	0.02*
	Latency	U = 21.50 z = -0.65	0.53
RM	Amplitude	U = 10.00 z = -2.00	0.05
	Latency	U = 22.50 z = -0.53	0.61

Taken together with the results looking at across-group stimulus effects for 15ms versus 90ms rise times, these results indicate that whilst the N1s of dyslexic children are responding in a similar way to the controls when the incoming stimulus has a short rise time, when the rise time is longer, the dyslexic N1 is suggestive of reduced neural efficiency.

8.3.3 Relationships between N1 response and behavioural performance

A further aim of this experiment had been to explore associations between N1 responses and the behavioural profiles of children across auditory processing, phonological and literacy measures. To this end whole group (n=15) Spearman's rho correlations were carried out between the LM and RM N1 amplitudes (these being the temporal electrodes of maximal signal) and seven theoretically-motivated behavioural measures.

The first two behavioural measures were the auditory processing tasks of rise time hit rate and AEO discrimination threshold. Despite the simplicity of the first measure, following from previous literature, correlations between ERP responses and behavioural responses to the same sounds were predicted (e.g. Kraus, McGee, Carrell, Zecker, Nicol & Koch, 1996, Menell & McAnally, 1999). Inclusion of the AEO discrimination threshold variable was interesting in order to compare the strength of N1 association with a measure also assessing the ability to hear rise time differences, though using different stimuli and presentation format.

Because sensitivity to AEO rise times is hypothesised here to directly affect phonological representation establishment, three measures of phonological processing were also entered into the correlation matrix, oddity, paired associate learning (PAL) and RAN (as used in the Phase 2 regression analyses focusing on behavioural auditory processing measures). Finally, the literacy measures of reading and spelling were included. The correlation matrix is presented in Table 8.8.

Strong correlations can be seen between 15 LM, 90 LM and 90 RM N1 responses and the AEO discrimination task. This association gives encouraging evidence of the link between ERP measures and behavioural performance, also supporting the construct validity of the AEO discrimination measure. There is also a correlation between the rise time hit rate measure and AEO discrimination, though rise time hit rate does not correlate with the ERP variables. This may be due to task insensitivity, as alluded to earlier in section 8.3.1.

Of further interest are the associations between the N1 responses and phonological awareness and literacy measures. These associations are particularly strong between the LM electrode (both 15ms vs. 90ms) and spelling, oddity and PAL.

Table 8.8 Spearman's rho correlations between N1 amplitude and selected behavioural measures.

	Read	Spell	Odd	PAL	RAN	AEO D	Hit rate	15 LM	15 RM	90 LM	90 RM
Read		0.80***	0.86***	0.74***	-0.63*	-0.47	0.26	0.54*	0.20	0.51	0.44
Spell			0.89***	0.81***	-0.60*	-0.55*	0.34	0.74**	0.47	0.71**	0.63*
Odd				0.83***	-0.68**	-0.52*	0.33	0.80***	0.37	0.67**	0.54*
PAL					-0.60*	-0.46	0.30	0.68**	0.23	0.62*	0.51
RAN						-0.07	-0.17	-0.36	-0.20	-0.03	-0.11
AEO D							-0.56*	-0.64*	-0.44	-0.77**	-0.66**
Hit rate								0.44	0.43	0.35	0.16
15 LM									0.77**	0.82***	0.81**
15 RM										0.53*	0.73**
90 LM											0.88***
90 RM											

***p< .001, **p< .01, *p< .05

Note: Read = BAS Reading, Spell = BAS Spelling, Odd = Oddity phonological awareness task, PAL = Paired associate learning, RAN = Rapid Autonomised Naming, AEO D = AEO discrimination threshold, Hit Rate = rise time hit rate score, 15 LM = Mean N1 amplitude at LM for 15ms stimuli, 15 RM = Mean N1 amplitude at RM for 15ms stimuli, 90 LM = Mean N1 amplitude at LM for 90ms stimuli, 90 RM = Mean N1 amplitude at RM for 90ms stimuli

8.4 Discussion

The primary goal of this chapter was to characterise the neural correlate of the AEO rise time insensitivity observed in dyslexic children, itself strongly associated with literacy skill. The N1 ERP response was investigated here. This is thought to index the earliest stage of stimulus-specific cortical encoding. Examining N1a responses at the temporal electrode sites, the results showed that whilst the typically-developing readers manifested a reduced amplitude response for the longer rise time stimuli, as seen in comparable studies with adults, the dyslexic group did not show an effect of stimulus. The dyslexic N1 response remained at the higher amplitude level for both stimulus rise times. This suggests that even at a very early level of auditory perceptual processing, the dyslexic brain is encoding stimulus onset information, specifically, AEO rise time information, with less sensitivity than age-matched peers.

There are at least two implications arising from this rise time insensitivity. Firstly, from what we understand about speech perception, rise times of the overall speech amplitude envelope yield important syllabic segmentation cues, by cueing the listener as to where vowel onsets are occurring (Scott, 1993). If dyslexic individuals are not making the same encoding distinctions at this supra-segmental level as their peers, then one might predict that the subsequent degree of contrastive phonological information they can store in their long-term phonological representations will be reduced.

A second implication arises from the observation that the dyslexic individuals are not only failing to make the same processing distinction as their peers, but that their response to stimuli that are less perceptually salient is just as strong as their response to a short, abrupt signal. Such an exaggerated response may already reflect a neural compensation for processing weakness, although this possibility can not be confirmed or otherwise from the current results.

These findings raise questions as to developmental nature of the processing differences observed. Earlier in development neural differences may also be present. We can not, however, state with any certainty whether these differences would look similar to these found at school-age, after a decade of speech input and many years of active exposure to print have also played a role in determining each individual's developmental trajectory. Future investigations must explore this issue.

A final aim of this experiment had been to explore associations between N1 responses and behavioural performance. When looking at the children across groups, N1 peak amplitude, especially to the sounds with longer rise times, was highly associated with behavioural rise time discrimination as indexed by the AEO discrimination task, as well as showing associations with phonological processing and literacy measures. Although replication of these results is required with a larger sample size of children, such results point towards the potential usefulness of ERP recording in assessing the auditory processing ability of young children, or those for whom behavioural testing is problematic. Thus, it can be used to determine the developmental time course of auditory processing difficulties, as well as the implications for phonological and literacy development. Because auditory processing is a complex and dynamic skill, with a maturational course that extends throughout childhood it may well be that different auditory strengths and weaknesses have impacts at different critical windows of a child's development.

Chapter 9 - General Discussion

9.1 Introduction

This thesis has set out to test and elaborate the Phonological Representations Hypothesis of developmental dyslexia, through cognitive, sensory and neural investigation. The Phonological Representations Hypothesis (PRH) of dyslexia proposes that all the phonological processing difficulties seen in dyslexia stem from underspecified phonological representations. The primary questions addressed in this thesis were:-

1) The PRH requires that the relationship between representation specificity and phonological processing be word–specific. Can evidence be found for word-specific associations between phonological representation quality and performance on input and output phonological processing tasks?

2) Underspecified phonological representations could arise because lexical factors act differently in developmental dyslexia. Can an in-depth exploration of phonological neighbourhood density effects inform our understanding of why dyslexic children's phonological representations are underspecified?

3) Underspecified phonological representations may arise from a more basic sensory deficit. Can an auditory processing deficit, specifically, amplitude envelope onset sensitivity, explain the phonological representation deficit in dyslexia?

Each of these questions and the evidence provided by this thesis is discussed in the following section.

9.2 Summary of Experimental Findings

9.2.1 Can evidence be found for word-specific associations between phonological representation quality and performance on input and output phonological processing tasks?

The experiments of Chapter 5 addressed this question. Taking picture naming as an index of phonological representation quality, significant differences in performance were found in the dyslexic group for both input (auditory visual lexical decision) and output (nonword repetition) phonological processing tasks, dependent upon whether the familiar lexical item could be correctly named. Dyslexic children achieved greater accuracy for items that could be named. In a vowel substitution task, which demands strong phoneme awareness, group differences also disappeared between the dyslexic group and their age-matched peers if only correctly named items were considered.

The auditory visual lexical decision and nonword repetition results are strongly supportive of Constable et al.'s work reporting word-specific associations between phonological representational quality and phonological processing. In addition, the results of the phonological awareness task (vowel substitution) suggest that when representational quality is controlled for, dyslexic children can perform at the level of their peers at phoneme level. This finding differs from that of Swan and Goswami (1997b). These authors found that even after adjusting for representational quality, a dyslexic deficit in phoneme awareness remained. The two results are not mutually exclusive, however, and perhaps highlight how differing task difficulty and group membership can affect experimental outcomes. The results obtained with the vowel substitution task are very exciting, as they suggest that in a supportive environment and carefully structured curriculum dyslexic children have the potential to achieve age-appropriate phonological awareness skills. The result also compellingly supports the Phonological Representations Hypothesis. A strong prediction of the PRH is that for well-specified phonological representations a phonological processing deficit should not be seen. This was the result obtained here.

9.2.2 Can phonological neighbourhood density inform our understanding of why dyslexic children's phonological representations are underspecified?

Having confirmed that in dyslexia phonological processing is determined by word-specific phonological representation specificity this thesis then explored the issue of why some representations are better specified than others. Lexical factors such as word frequency have already been shown to affect processing in tasks that require access to phonological representations. Here the relatively un-investigated factor of phonological neighbourhood density was explored. Lexical items with many phonological neighbours may face more pressure to become fully specified, to allow phonological differentiation between similar-sounding neighbours. It was of interest to see whether or not dyslexic children showed sensitivity to phonological neighbourhood density as altered sensitivity might explain why dyslexic phonological representations are less well-specified than those of their peers. Chapter 6 showed that across a variety of phonological processing tasks the dyslexic children were just as sensitive to phonological neighbourhood density as both their age matched and reading level matched peers. This was even true in a phonological learning paradigm (paired associate learning). The experiments here manipulated rime neighbourhoods and so we can conclude that dyslexic children organise their mental lexicons in a typical way for phonological units such as onsets and rimes. This does not rule out the possibility that more subtle phonological organisation deficits exist. Section 9.5 of this thesis outlines further work that could address this issue.

9.2.3 Can a more basic auditory processing deficit, specifically, amplitude envelope onset sensitivity, explain the phonological representation deficit in dyslexia?

As well as looking at cognitive reasons for the phonological representation deficit in dyslexia, this thesis also examined candidate perceptual causal mechanisms. In chapter 7 a new auditory candidate was proposed – amplitude envelope onset (AEO) perception. The rationale for investigating this auditory parameter was its hypothesised importance as a property of speech rhythm, speech rhythm helping to distinguish words as units within the speech stream. Using non-speech stimuli that varied in AEO rise time, group differences were found between the dyslexic children and age matched children, with the dyslexic children less sensitive to AEO rise time variation especially as rise time was prolonged. These differences were found across different psychoacoustic tasks and over a two-year study period. Strong concurrent relationships were demonstrated with phonological and literacy skills. In chapter 8 sensitivity to AEO rise time was assessed using a neurophysiological tool, event-related potential (ERP) recording. Analysis of ERPs showed that whilst the neural responses of the dyslexic children were the same as age matched controls when the AEO rise time was short, for longer rise times the dyslexic children did not show the expected reduction in N1 amplitude. This suggests an insensitivity to rise time at a very early level of sensory processing, possibly equivalent to initial stimulus-specific encoding. It also highlights a difference in processing when the AEO rise time of a stimulus is prolonged, i.e. the amount of salient acoustic information as a function of time is reduced. Further work must ascertain the role of AEO rise time in relation to other supra-segmental cues such as duration, as well as finding converging evidence from studies including speech as well as non-speech stimuli.

9.2.4 Phonological Representations In Dyslexia: Nature, Influences and Development

To summarise so far, the results presented here suggest that the normative development of phonological representation specificity for individual words is affected by dynamic interactions between cognitive (e.g. neighbourhood density) and perceptual (e.g. AEO sensitivity) influences: greater phonological specification occurs in dense phonological neighbourhoods, whilst accurate perception of AEOs may also facilitate the establishment of well-specified representations. Dyslexic individuals have a greater proportion of underspecified phonological representations than good readers. In the findings reported here, whilst the dyslexic group could benefit similarly to their controls from dense phonological neighbourhoods, they were more likely to have difficulty perceiving differences in amplitude envelope onsets. Higher proportions of underspecified phonological representations in dyslexia are therefore associated with perceptual limitation.

In order to understand this association further, it is important to consider feasible neuro-cognitive mechanism that could account for this finding. Recapitulating what we currently know about the nature of phonological representations, in the first chapter of this thesis phonological representations were described as abstract entities, with no invariant relationships existing between the acoustic input signal and phonological units. A phonological representation must encode both the information needed for accurate production as well as the degree of detail required to know which perceived forms to accept/reject as targets. Current conceptualisations of phonological representations differ in how much detail they believe representations to contain. At one extreme are theorists such as Hintzman (1986), proposing that representations may encode many multiple traces of speech input, in order to allow recognition and production across a diverse range of contexts. Other researchers suggest that representations may be more underspecified than this and that this underspecification allows the accommodation of a range of variant input forms (e.g. Stackhouse & Wells, 1997; note that *underspecificity* in this context is distinct from the reduced specificity in dyslexia, which refers to dyslexics' *relative* underspecificity in relation to typically-developing peers).

Neuro-cognitive models perhaps offer the most promising way to conceptualise phonological representations and loci of impairment. A notable example in this regard is Adaptive Resonance Theory (Grossberg, Boardman & Cohen, 1997; Grossberg, 2003). Grossberg and colleagues have posited a series of models related to speech recognition. Common to all is a system whereby speech input activates neuronal 'resonances' with similar chunks of phonological information in the neural networks subserving short-term memory. These *list chunks* can be phoneme-size chunks, onsets/rimes, syllables and words. Further important attributes are that larger size chunks are hypothesised to mask smaller ones and parallel list chunks compete amongst one another via lateral inhibitory links. List chunks are also purported to form the architecture of long-term memory storage. In these models word recognition depends upon an equilibrated resonant state in response to input. Thus, phonological representations are essentially patterns of neural activation precipitated by 'bottom up' input that become unitised through top-down expectancy systems that build up over time.

The testing and application of theories such as ART provide exciting possibilities for research concerning phonological representations. Vitevitch and Luce (1999), for example, have used ART to accommodate observations of phonological neighbourhood density effects in adult word recognition. The authors focus particularly on the idea of lateral inhibition between similar list chunks. They suggest that in recognition tasks words from dense phonological neighbourhoods will be recognised more slowly as there will be greater lateral inhibition from competing, similar phonological forms (or 'list chunks') as compared to words from sparse phonological neighbourhoods.

ART is also beginning to account for how speech perceptual systems deal with variance inherent to the input signal. Grossberg and coworkers have, for example, looked at how ART can model rate-independent speech perception by means of a neural 'gain control' system. Different speakers and environmental/linguistic contexts also cause other variations to the speech signal that must somehow be 'normalised' by the perceptual system. Further integration of neuro-cognitive models such as ART with existing psycholinguistic models could help account for a wider range of representational questions. One example informative to dyslexia would be to explore how perception of native vs. non-native phonological contrasts can be modelled. Existing psycholinguistic models such as Best's Perceptual Assimilation Model ('PAM', Best, 1994) state that in the course of development, perceptual biases develop towards the prototypical phoneme feature clusters of one's native language. As well as determining the degree of allophonic variation acceptable for a certain phonemic category, this mode of perception allows for more efficient processing of cues that determine category membership (*between* category cues) versus *within* category phonetic contrasts.

In a very recent paper, Serniclaes, Heghe, Mousty, Carre and Sprenger-Charolles (2004) have suggested that dyslexic children may have *higher* sensitivity to phonetic distinctions *irrelevant* within their linguistic environment. This would mean that normal perceptual biases have not developed to the same degree in these children. This would result in difficulty processing phonological variants of a single phoneme such as the alveolar /l/ in 'light' versus the velar /l/ of 'ankle', which is produced with a more posterior tongue position. Normal perceptual biases result in these allophonic variants being processed as the same phoneme. Serniclaes et al. propose that in dyslexia the ability to group these perceptually distinct variants may be impaired. The creation of a testable neural model related to the development of native language perceptual biases would thus allow such hypotheses to be examined further.

If speech perception involves the comparison of incoming speech to neural resonances shaped by previous perceptual experience then it is also possible to hypothesise how insensitivities to AEO variation might affect such a system. This thesis has discussed how the ability to detect AEOs will allow infants to attune to the basic rhythm of the speech stream, determined by the 'beats' of syllables. Note also that this rhythm is particularly emphasised in caregivers' speech to young children through "motherese". The ability to perceive the syllabic structure of speech stream will then allow more fine-grained sub-syllabic analysis to occur. Thus AEO sensitivity could feasibly be critical to the initial establishment of input-to-neuron resonances.

Such models are clearly speculative, however trying wherever possible to link cognitive processes to feasible neuroscience mechanisms will be a promising way to further our knowledge and reduce the 'black box' nature of phenomena like phonological representations. In order to fully understand difficulties such as dyslexia it is imperative we go beyond this.

9.3 Implications for Education

A key finding of this study in educational terms is acknowledgment of the phonological awareness strengths that dyslexic children can have in a supported context. The work of Swan and Goswami (1997b) previously highlighted how dyslexic children could perform at levels equivalent to their peers in syllable and onset-rime level phonological awareness tasks. This was possible when children had well-specified phonological representations for words and greater specification occurred for shorter length and higher frequency items. The current thesis extends this finding. When the level of phonological specification is controlled for dyslexic children can even match their peers in phoneme-level task performance. Teachers can thus use this knowledge when creating graded schemes of work, to play to children's strengths as well as address areas of weakness.

Another finding with important practical implications is the demonstration of greater specification for lexical items in dense phonological neighbourhoods. Neighbourhood density properties of words are not always immediately obvious, for example it would be hard to know without reference to a database that the word 'wake' has many more neighbours than the word 'like'. For a teacher planning literacy hour therefore, being explicitly informed of this information could help when grading the difficulty of phonological awareness activities. This grading would then help ensure children's ability to achieve a certain criterion of success.

A final key educational implication is that provided by the evidence of a link between AEO, or 'beat' sensitivity tasks and literacy across reading ability groups. This finding re-iterates the importance of activities that reinforce rhythmic perception and production. For optimal transfer of learning this would probably be most beneficial within a linguistic context, for example games highlighting the rhythmic stress patterns of the native language (strong-weak syllable stress in English). Further applied research studies are required to examine these possibilities.

9.4 Limitations of the current thesis

One limitation of this thesis relates to experimental task sensitivity. In chapter 5 the degree of phonological representation specificity at syllable, onset-rime and phoneme levels was assessed using a picture matching task that basically turned out to be too easy to show performance differentiation dependent upon representational integrity. In Phase 2 of the assessments this problem was circumvented however, by focusing upon the most challenging phonological level, that of the phoneme, and introducing a more demanding task, vowel substitution. The same problem of task insensitivity arose for the short term memory task used at Phase 2 to investigate phonological neighbourhood density. Interpretable results were, however, available from concurrent tasks also manipulating neighbourhood density. Greater consideration of reaction time data, alongside the accuracy data reported here could have increased task sensitivity.

In relation to the investigation of amplitude envelope onset sensitivity, the inclusion of more comparison auditory processing tasks would strengthen the current findings. A factor not controlled for in the stimuli used was the overall intensity of the stimuli, which will increase when the AEO rise time is shortened. In Appendix 6 an ERP pilot study is reported in which AEO rise time variation was investigated with overall stimulus intensity controlled, however in this pilot study the stimuli were very short and so for longer stimuli intensity equivalence is harder to achieve. An alternative solution would be to include a behavioural control task, equivalent in task demand to the AEO measure, which assessed overall intensity sensitivity (see Richardson et al., 2004)

Although AEO rise time is an important property of speech rhythm it will also be useful to look at the contribution of other rhythmic cues such as duration and amplitude modulation frequency/depth. This will allow more direct comparisons with the findings of previous studies (e.g. Lorenzi et al., 2000; Rocheron et al., 2002) as well as confirming that the effects seen are attributable specifically to AEO rise time variation. Cross-language studies would also be useful in this regard as these would enable one to see whether different rhythmic cues have differential salience according to the prosodic structure of a given language.

A further limitation of this thesis relates to the small subject numbers in the ERP experiment of chapter 8. Data from further subjects is clearly imperative, both to increase the power of the reported N1 results, as well as to enable examination of the MMN, 'change detection' component. As well as recording the N1 in the oddball ERP paradigm reported here it would also be informative to look at the nature of N1 responses when stimuli are presented in other paradigms, for example, using an equal probability design.

9.5 Directions for future research

As well as overcoming the limitations outlined above, an additional important goal for future research should be to develop more sensitive measures of phonological representation specificity. Picture naming accuracy has proved informative in this and other studies, however there is much scope for task refinement. The correctness criteria used in this thesis accepted realisations of items that were within the accepted phonemic boundaries of English, however more in-depth spectrographic analysis could inform us as to the presence or absence of 'sub-clinical' phonological output differences between dyslexics and their age peers. Underspecified phonological representations have often been called 'fuzzy' in the existing literature – more fine-grained analysis might allow us to go beyond vague descriptives such as this. The work of Elbro (1996; 1998), looking at vowel reductions in the phonological realisations of dyslexics highlights the possibilities of such research. Other ways to think about phonological specification that go beyond phoneme level representation are to develop measures of more implicit areas of phonological processing, such as accent processing (Nathan, Wells & Donlan, 1998), syllable stress placement (cf. Wood, 2004) and dealing with allophonic variation (Serniclaes et al., 2004). With recent studies reporting word-specific cortical activity reflected in MMN paradigms (Pulvermuller, Shtyrov, Kujula & Näätänen, 2004) it may also be possible to design paradigms examining phonological specificity using techniques such as ERP. This would allow investigation of phonological representation integrity in the absence of the motor output demands that are inherent to picture naming.

In thinking about causal mechanisms for the underspecified phonological representations in dyslexia this thesis has focused upon perceptual factors, such as amplitude envelope onset sensitivity. Phonological development does not occur through perceptual input processing alone however, but rather progresses through the interplay of sensory input, motor output and the feedback processes that link the two. An important future direction from this work would be to consider the implications for phonological output processes of an insensitivity to amplitude envelope onsets. Related to this, it will also be critical to extend the findings concerning nonspeech AEO sensitivity to more speech-like stimuli in both perceptual and productive experimental paradigms. If further supportive evidence was found for the important role of AEO sensitivity, an intervention study could then examine whether AEO sensitivity was trainable and if so, would benefits for phonological representation specificity and literacy also be observed. In addition, the use of ERP recording as a tool for measuring pre-attentive responses to AEO variation could be extended to see whether patterns of neural response change as a result of remediation as suggested by recent studies focusing upon different auditory parameters (Kujala, Karma, Ceponiene, Belitz, Turkkila, Tervaniemi & Näätänen, 2001).

It will also be important to explore AEO rise time processing at developmentally earlier stages, both behaviourally as well as neurophysiologically. Studies of children at risk of dyslexia have found reliable ERP group differences to spoken syllables between at-risk and non-risk newborns (Leppänen, Pihko, Eklund & Lyytinen, 1999; Guttorm, Leppänen, Richardson & Lyytinen, 2001). Similar investigations looking at a wider range of auditory parameters, such as AEO sensitivity may help isolate neural markers of dyslexia risk. Steps can then be taken to minimise the impact of this risk, such as improving the home literacy environment and strengthening known literacy precursors such as phonological awareness, including devising training programmes actively manipulating factors such as phonological neighbourhood density.

9.6 Conclusion

The key message of this thesis is that to understand dyslexia further, research should look beyond phoneme level deficits. Although phonemic, or segmental, level representation appears impaired in dyslexia, the causal mechanisms of this deficit may be determined by perceptual processes operating over larger, supra-segmental, time windows. A parameter explored here was sensitivity to amplitude envelope onsets. The rate of AEO rise time depends both on the stress given to a syllable, the particular onset and vowel of that syllable as well as how the speaker articulates the sounds. Insensitivity to this parameter may make it more difficult to set up a well-specified phonological system, whilst the inherent variability of the speech signal e.g. when a speaker is unfamiliar or when there is noise will result in persistent processing weaknesses. In dyslexia such an insensitivity appears mild. Speech and language can thus develop within normal developmental limits, however in literacy acquisition, which requires highly specified phonological representation, deficits are observed. If the auditory processing deficit is more extreme, the resultant phonological representation deficits may cause speech and language difficulties. Future research that takes a much wider phonological perspective on observed phoneme-grapheme correspondence difficulties in dyslexia will help to confirm or develop the ideas of this thesis further.

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Appendix 1. Target names and distracter foils for the object name recognition task

Target names	Visual Foils	Semantic Foils	Phonological Foils	Control Foils
Short Length x High Frequency				
dust	sweep	polish	crust	mask
clock	watch	sun-dial	lock	wreath
flag	handkerchief	flag-pole	tag	tongs
frame	rectangle	door	flame	sphynx
pipe	cigarette	match	pine	bench
queen	fairy	throne	quill	ramp
chain	rope	bicycle	brain	scroll
globe	ball	map	robe	noose
tent	pyramid	caravan	vent	latch
belt	sash	trousers	melt	dart
Long Length x High Frequency				
exercise	waving	trainers	fries	candelabra
television	microwave	aerial	telescope	pendulum
electricity	sparks	socket	city	pyramid
potatoes	onions	chips	tomatoes	volcano
factory	hospital	smoke	battery	asparagus
triangle	coat-hanger	square	tricycle	palette
audience	queue	stage	fence	seahorse
alphabet	numbers	book	vet	compass
hospital	factory	ambulance	bottle microscope	muzzle
telescope	cylinder	magnifying glass		hammock
Short Length x Low Frequency				
vest	waist-coat	shirt	crest	tripod
quill	fern	pen	drill	raft
claw	tongs	pliers	jaw	trellis
maze	hedge	street-map	cage	stilts
yawn	shout	bed	prawn	igloo
moat	lake	bridge	throat	acorn
harp	lamp-post	orchestra	hatch	medal
whisk	spoon	eggs	disk	cactus
wick	string	match	tick	racquet
clog	shoe	foot	cog	antlers
Long Length x Low Frequency				
propeller	windmill	aeroplane	umbrella	ambulance
protractor	ruler	angle	tractor	accordion
binoculars	microscope	telescope	monocle	toboggan
harmonica	pencil case	whistle	harbour	stethoscope
boomerang	stick	kangaroo	loom	pyramid
tentacles	snakes	ocean	tee-pee	propeller
banister	ladder	stairs	blister	abacus
dominoes	dice	chess	dome	unicorn
escalator	railway-track	stairs	elevator	artichoke
acrobat	trapeze artist	circus	accident	rhinoceros

Appendix 2. Full list of stimulus items used in phonological awareness tasks.

Mean frequencies per column shown in bottom row of each grid, standard deviations in parentheses. Frequency counts per million in brackets, from Zeno, Ivens, Millard & Duvvari (1995).

i) Syllable, Long Length

High Frequency			Low frequency		
Cue	Target	Distracter	Cue	Target	Distracter
hamburger	telescope	calculator	protractor	xylophone	caterpillar
computer	hospital	America	banister	crocodile	radiator
policeman	alphabet	operation	propeller	tentacles	ballerina
television	thermometer	medicine	binoculars	accordion	cucumbers
helicopter	supermarket	furniture	harmonica	rhinoceros	typewriter
conversation	arithmetic	skeleton	escalator	invitation	umbrella
31.32 (26.14)	21.83 (19.76)	39.33 (27.39)	1.33 (0.52)	3.00 (2.68)	3.83 (2.56)

ii) Syllable, short length

High Frequency			Low frequency		
Cue	Target	Distracter	Cue	Target	Distracter
belt	lamp	baby	yawn	pear	yoyo
bridge	cheese	button	lung	vase	lego
heart	fence	happy	calves	whisk	camel
sugar	penny	shark	sandal	polish	shorts
wagon	ruler	whale	tissue	wizard	tights
cherry	finger	church	pizza	lemon	punch
65.17 (55.06)	30.67 (10.97)	67.47 (54.17)	5.63 (4.77)	5.83 (5.12)	4.50 (4.81)

iii) Rime

High Frequency			Low frequency		
Cue	Target	Distracter	Cue	Target	Distracter
flag	bag	hat	moat	goat	boot
clock	rock	shop	wick	chick	knit
pipe	type	rope	quill	frill	scroll
globe	robe	nose	clog	bog	sock
frame	game	moon	lawn	prawn	sword
queen	bean	train	claw	drawer	prayer
whale	tail	bowl	whisk	disc	mask
31.00 (10.95)	85.43 (64.16)	94.10 (42.71)	1.57 (0.79)	2.43 (1.81)	4.60 (3.03)

iv) Onset singleton

High Frequency			Low frequency		
Cue	Target	Distracter	Cue	Target	Distracter
tent	tape	duck	vest	van	fair
dust	doll	bat	maze	mug	vase
belt	ball	pan	harp	hare	beige
chain	cheese	shop	dice	dove	toad
hill	heart	sun	boot	bin	palm
match	mouse	bike	torch	tyre	dart
soap	sail	fork	cheek	chess	cot
47.71 (24.18)	69.43 (63.76)	73.99 (123.51)	4.29 (3.15)	3.14 (1.77)	3.43 (2.51)

v) Onset cluster

High Frequency			Low frequency		
Cue	Target	Distracter	Cue	Target	Distracter
queen	cap	wing	quill	cork	wand
clock	cage	lamp	clog	comb	lung
globe	gun	laugh	claw	cog	lace
flag	foot	log	plug	pear	lock
swim	salt	wheel	swan	seal	whip
snake	sad	nose	grill	golf	rake
glass	ghost	leaf	tray	tusk	wrist
58.73 (44.17)	64.39 (45.25)	49.71 (27.47)	3.77 (3.30)	4.43 (4.26)	4.92 (3.58)

vi) Final consonant singleton

High Frequency			Low frequency		
Cue	Target	Distracter	Cue	Target	Distracter
frame	thumb	spoon	maze	hose	dice
pipe	rope	suit	yawn	van	toad
chain	pan	worm	harp	zip	lock
shell	doll	card	moat	cot	chalk
dog	bag	tick	wick	sack	tart
hat	foot	cup	wig	plug	rake
knife	leaf	dress	snail	hole	prawn
74.20 (71.49)	59.50 (48.12)	44.54 (11.08)	2.36 (1.97)	5.73 (4.07)	5.20 (3.83)

vii) Final consonant cluster

High Frequency			Low frequency		
Cue	Target	Distracter	Cue	Target	Distracter
dust	note	mice	vest	flute	kiss
tent	bat	gun	whisk	sock	chess
belt	coat	hill	ramp	hop	sum
milk	rock	well	kilt	dart	mole
nest	shirt	bus	punch	torch	bin
gold	sad	nail	hump	whip	jam
fence	rice	man	fold	hood	pill
73.61 (48.84)	70.76 (44.76)	181.47 (348.79)	3.21 (2.71)	2.41 (1.60)	3.76 (2.46)

Appendix 3. Multiple regression tables to accompany section 5.3.5

	DV: Reading		
	Beta	t	p
1: Age	0.23	2.16	0.034
2: Blocks	0.09	0.89	0.373
3: Vocab	0.19	1.53	0.131
4: Naming	0.32	2.62	0.011

	DV: Reading		
	Beta	t	p
1: Age	0.14	1.58	0.118
2: Blocks	0.05	0.55	0.581
3: Vocab	0.19	1.95	0.056
4: AVLD	0.55	5.79	0.000

	DV: Reading		
	Beta	t	p
1: Age	0.32	3.25	0.002
2: Blocks	0.13	1.24	0.220
3: Vocab	0.22	2.05	0.045
4: NWR	0.40	3.91	0.000

Key:

AVLD = Auditory visual lexical decision
NWR = Nonword repetition

Note. DV = Dependent variable

DV: Reading			
	Beta	t	p
1: Age	0.14	1.57	0.120
2: Blocks	0.05	0.55	0.582
3: Vocab	0.19	1.81	0.074
4: Naming	-0.02	-0.15	0.882
5: AVLD	0.56	4.88	0.000

DV: Reading			
	Beta	t	p
1: Age	0.18	2.35	0.022
2: Blocks	0.02	0.20	0.842
3: Vocab	0.17	1.82	0.074
4: Naming	0.18	1.96	0.054
5: NWR	0.60	7.63	0.000

Key:

AVLD = Auditory visual lexical decision
NWR = Nonword repetition

Note. DV = Dependent variable

Appendix 4. Multiple regression tables to accompany section 7.3.4

	DV: Reading		
	Beta	t	p
1: Age	0.23	2.61	0.011
2: Blocks	-0.03	-0.26	0.796
3: Vocab	0.27	2.91	0.005
4: AEO	-0.54	-5.83	0.000

	DV: Spelling		
	Beta	t	p
1: Age	0.12	1.20	0.233
2: Blocks	-0.04	-0.40	0.687
3: Vocab	0.19	1.85	0.069
4: AEO	-0.54	-5.24	0.000

	DV: Reading		
	Beta	t	p
1: Age	0.14	1.33	0.188
2: Blocks	0.02	0.21	0.834
3: Vocab	0.31	2.90	0.005
4: RFD	0.36	3.28	0.002

	DV: Spelling		
	Beta	t	p
1: Age	0.07	0.61	0.542
2: Blocks	0.04	0.33	0.745
3: Vocab	0.24	2.04	0.046
4: RFD	0.23	1.85	0.068

	DV: Reading		
	Beta	t	p
1: Age	0.25	2.37	0.020
2: Blocks	0.05	0.42	0.675
3: Vocab	0.32	2.90	0.005
4: TOJ	0.26	2.40	0.019

	DV: Spelling		
	Beta	t	p
1: Age	0.14	1.25	0.218
2: Blocks	0.04	0.33	0.743
3: Vocab	0.24	1.99	0.050
4: TOJ	0.23	1.97	0.053

Key:

AEO = AEO detection
RFD = Rapid frequency discrimination
TOJ = Temporal order judgement

Note. DV = Dependent variable

DV: Nonword Reading	Beta	t	p
1: Age	0.08	0.71	0.482
2: Blocks	0.04	0.37	0.715
3: Vocab	0.09	0.85	0.401
4: AEO	-0.40	-3.46	0.001

DV: Oddity	Beta	t	p
1: Age	0.06	0.61	0.544
2: Blocks	0.17	1.48	0.144
3: Vocab	0.16	1.45	0.152
4: AEO	-0.39	-3.55	0.001

DV: Nonword Reading	Beta	t	p
1: Age	-0.03	-0.21	0.834
2: Blocks	0.05	0.39	0.691
3: Vocab	0.11	0.93	0.356
4: RFD	0.39	3.11	0.003

DV: Oddity	Beta	t	p
1: Age	-0.03	-0.23	0.862
2: Blocks	0.18	1.54	0.128
3: Vocab	0.17	1.54	0.128
4: RFD	0.35	2.91	0.005

DV: Nonword Reading	Beta	t	p
1: Age	0.10	0.85	0.399
2: Blocks	0.11	0.85	0.398
3: Vocab	0.13	1.02	0.310
4: TOJ	0.18	1.45	0.152

DV: Oddity	Beta	t	p
1: Age	0.07	0.65	0.52
2: Blocks	0.19	1.64	0.11
3: Vocab	0.19	1.60	0.11
4: TOJ	0.24	2.28	0.03

Key:

AEO = AEO detection
RFD = Rapid frequency discrimination
TOJ = Temporal order judgement

Note. DV = Dependent variable

DV: STM	Beta	t	p
1: Age	0.02	0.20	0.841
2: Blocks	-0.26	-2.21	0.031
3: Vocab	0.26	2.19	0.032
4: AEO	-0.37	-3.2	0.002

DV: RAN	Beta	t	p
1: Age	-0.35	-3.16	0.002
2: Blocks	-0.15	-1.29	0.200
3: Vocab	0.07	0.59	0.555
4: AEO	0.29	2.61	0.011

DV: STM	Beta	t	p
1: Age	-0.48	-0.39	0.695
2: Blocks	-0.24	-1.92	0.059
3: Vocab	0.28	2.29	0.025
4: RFD	0.28	2.22	0.030

DV: RAN	Beta	t	p
1: Age	-0.33	-2.68	0.009
2: Blocks	-0.20	-1.64	0.107
3: Vocab	0.04	0.32	0.753
4: RFD	-0.12	-0.94	0.353

DV: STM	Beta	t	p
1: Age	0.05	0.38	0.704
2: Blocks	-0.20	-1.57	0.120
3: Vocab	0.28	2.28	0.026
4: TOJ	0.16	1.32	0.190

DV: RAN	Beta	t	p
1: Age	-0.37	-3.25	0.002
2: Blocks	-0.23	-1.82	0.073
3: Vocab	-0.04	0.37	0.716
4: TOJ	-0.06	-0.51	0.609

Key:

AEO = AEO detection
RFD = Rapid frequency discrimination
TOJ = Temporal order judgement
STM = Short-term memory
RAN = Rapid automatised naming

Note. DV = Dependent variable

Appendix 5. Multiple regression tables to accompany section 7.7.4

	DV: Reading		
	Beta	t	p
1: Age	0.16	1.74	0.087
2: Blocks	-0.07	-0.74	0.460
3: Vocab	0.25	2.76	0.007
4: AEO	-0.48	-5.16	0.000
5: RFD	0.23	2.32	0.024

	DV: Reading		
	Beta	t	p
1: Age	0.16	1.74	0.087
2: Blocks	-0.07	-0.74	0.460
3: Vocab	0.25	2.76	0.007
4: RFD	0.23	2.32	0.024
5: AEO	-0.48	-5.16	0.000

	DV: Reading		
	Beta	t	p
1: Age	0.20	2.69	0.009
2: Blocks	-0.10	-1.25	0.217
3: Vocab	0.19	2.48	0.016
4: Oddity	0.46	5.31	0.000
5: AEO	-0.36	-4.23	0.00

	DV: Reading		
	Beta	t	p
1: Age	0.16	1.80	0.076
2: Blocks	-0.75	-0.84	0.404
3: Vocab	0.21	2.40	0.019
4: Oddity	0.55	5.92	0.000
5: RFD	0.17	1.81	0.075

DV: Reading	Beta	t	p
1: Age	-0.03	-0.27	0.787
2: Blocks	0.01	0.06	0.953
3: Vocab	0.37	3.09	0.003
4: AEO	-0.35	-2.99	0.004

DV: RAN	Beta	t	p
1: Age	-0.29	-2.41	0.019
2: Blocks	-0.34	-2.61	0.012
3: Vocab	-0.73	-0.60	0.549
4: AEO	0.23	1.89	0.063

DV: Spelling	Beta	t	p
1: Age	-0.04	-0.34	0.732
2: Blocks	0.05	0.41	0.86
3: Vocab	0.32	2.61	0.012
4: AEO	-0.34	-2.81	0.007

DV: PAL	Beta	t	p
1: Age	0.06	0.49	0.626
2: Blocks	0.14	1.13	0.266
3: Vocab	0.38	3.30	0.002
4: AEO	-0.34	-3.06	0.003

DV: Oddity	Beta	t	p
1: Age	-0.12	-0.95	0.344
2: Blocks	0.11	0.78	0.439
3: Vocab	0.28	2.21	0.031
4: AEO	-0.23	-1.88	0.066

Key:

AEO = AEO discrimination
RFD = Rapid frequency discrimination
TOJ = Temporal order judgement
PAL = Paired associate learning
RAN = Rapid automatised naming

Note. DV = Dependent variable

Appendix 6. ERP Pilot Study

Introduction

Two experiments are outlined below. The first investigates both the presence and nature of N1s to rise time variation in healthy adult listeners. The second experiment looks at the potential confound of rise time change with overall intensity change and a paradigm is described which attempts to separate the influences of these two related variables.

Experiment 1

Experiment 1 had two specific aims:-

1. To confirm the presence of varying N1 amplitude and/or latency responses to sound stimuli with short vs. long rise times.

2. To characterise the topography and hemispheric symmetry of the N1 responses to rise-time-varying stimuli.

Method

Participants

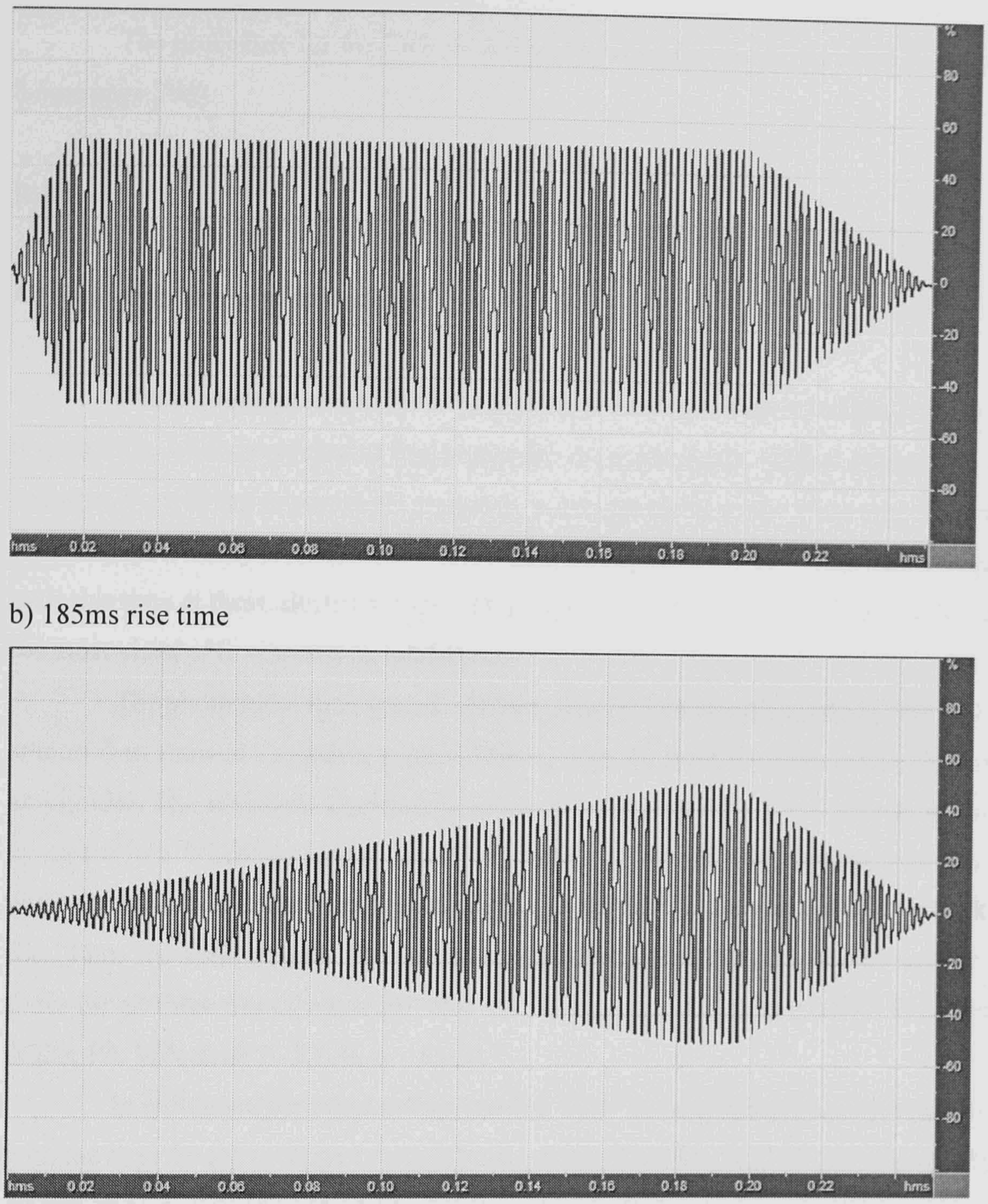
The participants were 12 healthy adults (5 males and 7 females) with a mean age of 26 years (range between 20-42 years). The volunteers were recruited from the author's university department at the Institute of Child Health, University College London.

Stimuli

The stimuli used were non-speech sine wave tones of 250ms duration with either short (15ms) or long (185ms) rise times. The stimuli were 500Hz in frequency and had a constant fall time of 50ms. Schematic diagrams of the stimuli used are shown in Figure A1.

Figure A1. Schematic diagrams of a) 15ms and b) 185ms rise time tones used in Experiment 1.

a) 15ms rise time



b) 185ms rise time

Experimental design

An oddball paradigm was used to elicit both N1 and MMN ERP components (MMN data will not be reported here). In this design 2 blocks of stimuli were presented to the participants. In Block A the long rise time stimulus was presented as a frequent standard whilst the short rise time stimulus was presented as an infrequent "deviant" stimulus (5% of trials). In Block B the short rise time stimulus acted as the standard whilst the long rise stimulus acted as the deviant. The stimulus-onset-asychrony (SOA) was 500ms and deviant stimuli were always preceded by at least 2 standards. Each block contained 1000 stimuli and was presented twice. A presentation order of ABAB or BABA was counterbalanced across participants. Each block lasted just over 8 minutes with an interval of at least 2 minutes separating them. Stimuli were presented binaurally through headphones. Participants' attention was diverted away from the stimuli through the watching of a self-selected silent video.

ERP recording and data processing

The procedure for the ERP recording followed in exactly the same way as described in Chapter 8 (see page 206).

Results

N1 responses to rise time variation

Grand averages across all individuals were computed for 15ms and 185ms rise time stimuli respectively, when presented as frequently occurring standards. Visual inspection of these grand averages showed the maximal N1 response, most prominent in the 15ms stimuli, to be at a fronto-central location, specifically at electrodes F3, Fz and F4. Figure A2 shows the grand average waveforms for each rise time at these electrode sites. This fronto-central response is also referred to as the N1b and is the most visible N1 response in adulthood.

The shorter rise time stimuli elicited a distinctive negative peak at 100-150ms. Both rise time stimuli then showed a negative peak at 250ms, with the short rise time consistently generating greater amplitudes. The statistical significance of the difference at 100-150ms post-stimulus onset was measured by means of a Wilcoxon Paired Rank Tests for each electrode site. Rather than measure peak amplitude and latency as in chapter 8, an area measure was taken. This was in view of the lack of visible peak for the 185ms rise time stimuli. The analysis confirmed a significant difference in N1 response between rise times for all three frontal electrode sites, F3, Wilcoxon Z -2.045, $p = 0.041$; Fz, Wilcoxon Z -2.28, $p = 0.023$; F4, Wilcoxon Z -2.118, $p = 0.034$.

In childhood the temporally-recorded 'N1a' is much more prominent and so for comparability with the experiment in chapter 8 the N1a responses from T5, T6, LM and RM are shown in Figure A3. As can be seen, this subcomponent is very small in adults. Visual inspection of the waveforms shows a small latency difference between the 15ms and 185ms rise time stimuli, with a longer latency for the longer rise time.

eeeeeeeeeeeere A2 Grand average waveforms for N1b responses to 15ms and 185ms rise time stimuli.

:::::::::::′: 15ms rise time 185ms rise time

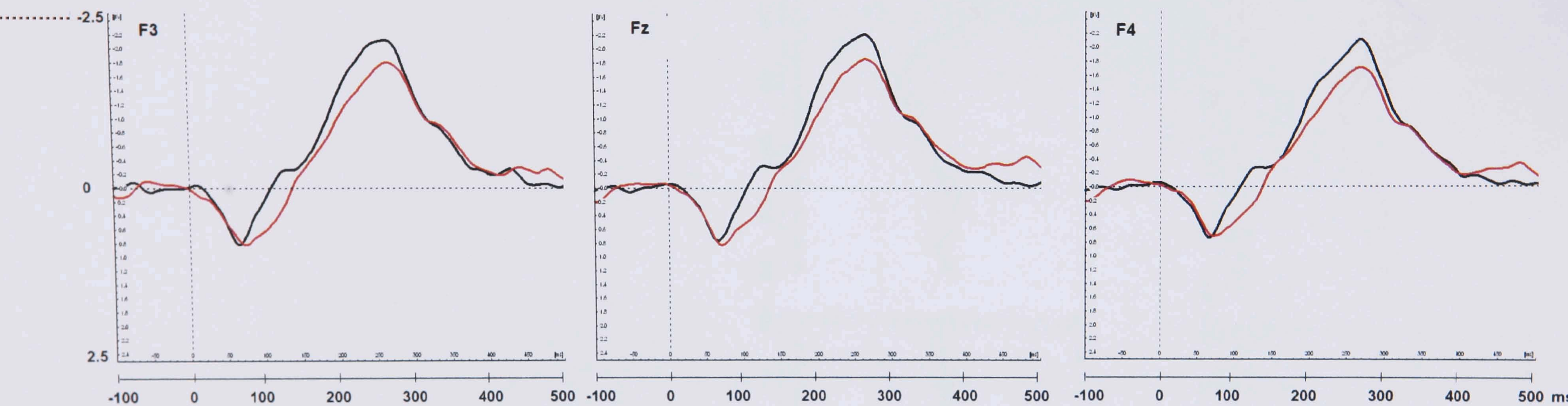
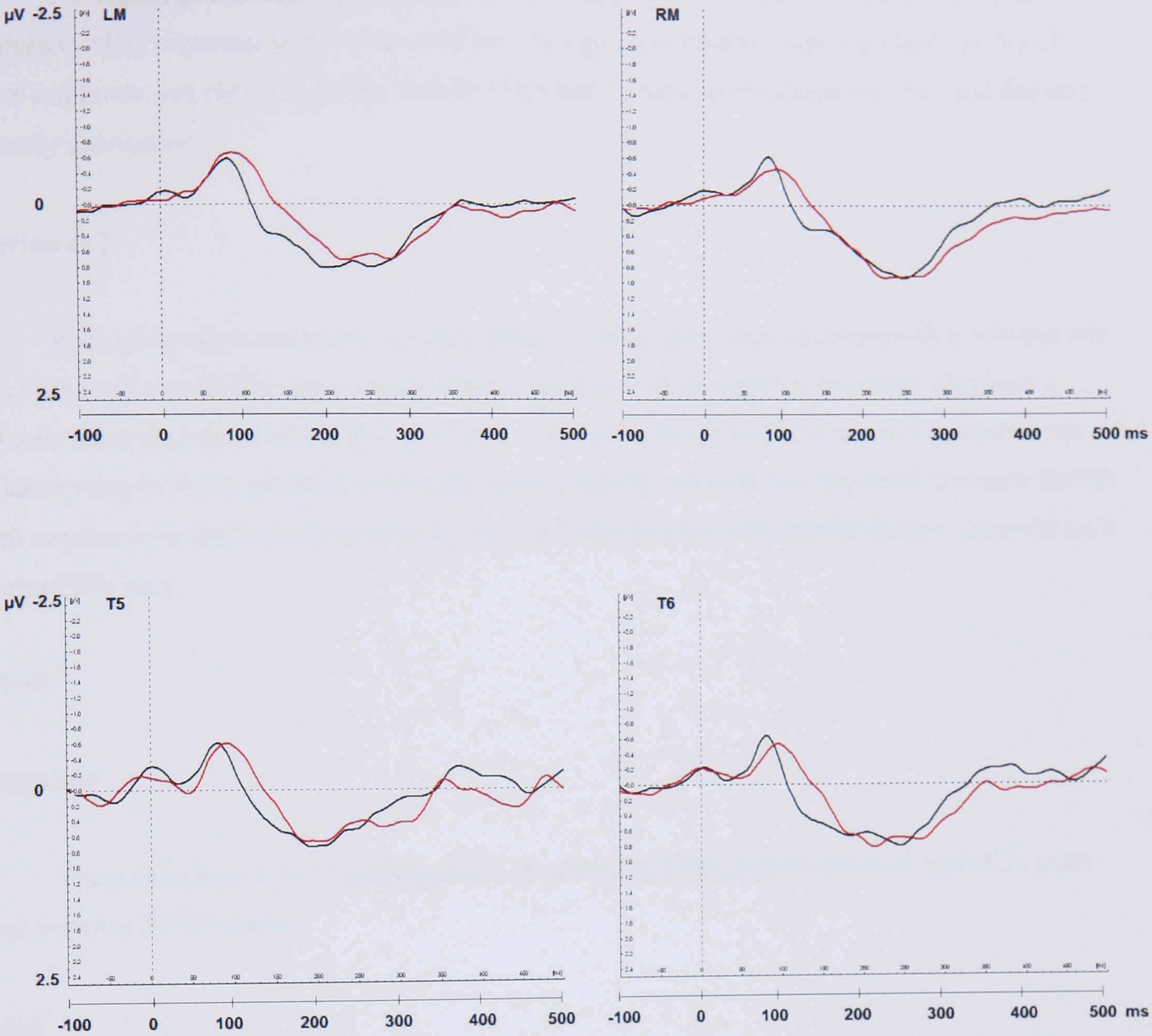


Figure A3 Grand average waveforms for N1a responses to 15ms and 185ms rise time stimuli.

KEY: 15ms rise time 185ms rise time



Summary of experiment 1 results

The results of this experiment confirm the findings of previous ERP studies which have examined cortical responses to rise time variation. In a group of healthy adult volunteers, an N1 of greater amplitude was observed for the stimuli which had a shorter more abrupt rise time and this was bilaterally distributed.

Experiment 2

In carrying out experiment 1 a further question arose, concerning the relationship between rise time change and overall stimulus intensity change. Stimuli with shorter rise times may also have a greater intensity than those with longer rise times. As well as being sensitive to onset characteristics it is also known that the N1 is sensitive to intensity more generally and so it was important to ensure that the neural responses we were recording were not just attributable to overall intensity change. Experiment 2 addressed this issue.

Method

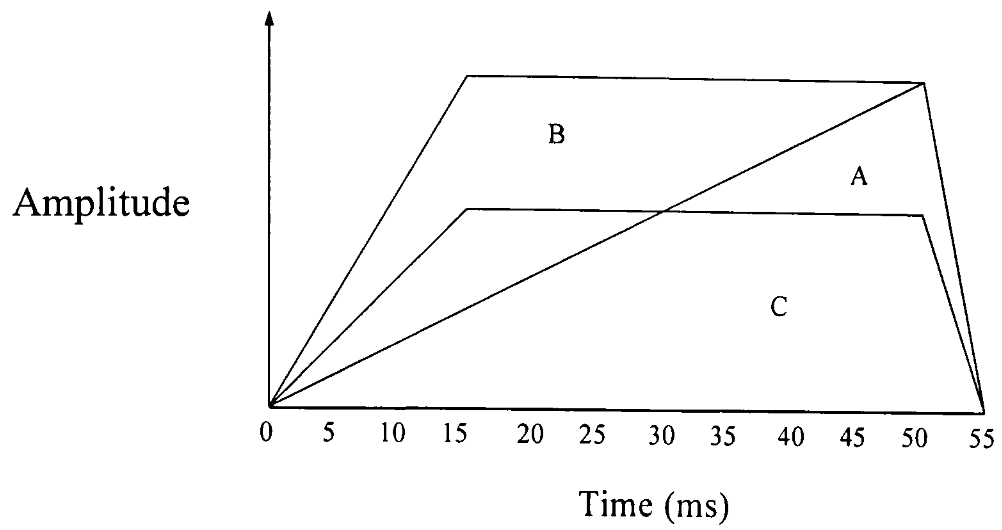
Participants

The participants were 11 healthy adults (3 males and 8 females) with a mean age of 24 years (range between 20-42 years).

Stimuli

Previous research suggests that the perceived loudness of a tone will increase quite abruptly with an increase in stimulus duration up to about 80ms (Scharf, 1978), a phenomenon known as loudness summation. The stimuli used in this experiment were designed to occur completely within this window of 'temporal integration' (Näätänen, 1990). The overall stimulus length was 55ms. The 'short' rise time stimuli had a rise time of 15ms (use of a shorter rise time might introduce unwanted spectral splatter and was thus contra-indicated). The 'long' rise time stimuli had a rise time of 50ms. A third stimulus was created which again had a short, 15ms rise time, however for this stimulus the overall intensity of the tone was matched to that of the longer rise time stimulus (thus reaching a slightly lower amplitude peak compared to the other stimuli). This third stimulus in effect counteracted the loudness summation effect. A schematic diagram of the three stimuli is shown in Figure A4.

Figure A4. Schematic diagram of tone stimuli showing A) Long (50ms) RT tone. B) Short (15ms) RT tone, with maximum amplitude peak equivalent to long RT tone (thus overall intensity greater). C) Short (15ms) RT tone, with maximum amplitude peak reduced (thus overall intensity equivalent to long RT tone).



The maximum amplitude of stimulus C was calculated mathematically using trigonometric functions and the perceptual validity of its intensity equivalence with stimulus A was also verified by behavioural testing of 10 additional adult volunteers in a same-difference judgement task. This task featured a continuum of 15ms rise time stimuli with varying amplitude maxima, presented alongside stimulus A. The stimuli were 500Hz, with a constant total duration of 55ms and fall time of 5ms. The results of this pilot test confirmed the perceived intensity equivalence of stimuli A and C.

Experimental design

As in experiment 1 an oddball design was used. In this design 2 blocks of stimuli were presented to the participants. In Block A the standards were 15ms rise time intensity-matched tones ('15IM'), whilst the deviants were either the 15ms rise time non-intensity matched ('15NIM') tones (5%) or the 50ms rise time stimuli (5%). In Block B the longer 50ms rise time stimulus acted as the standard whilst the deviants were either the 15IM tones (5%), or the 15NIM tones (5%). The stimulus-onset-asychrony (SOA) was 500ms and deviant stimuli were always preceded by at least 2 standards. Each block contained 1000 stimuli and was presented twice. A presentation order of ABAB or BABA was counterbalanced across participants. Each block lasted just over 8 minutes with an interval of at least 2 minutes separating them. Stimuli were presented binaurally through headphones. Participants' attention was diverted away from the stimuli via the watching of a self-selected silent video.

ERP recording and data processing

The procedure for the ERP recording followed in exactly the same way as described in Chapter 8 (see page 206).

Results

N1 responses to rise time variation

Grand averages across all individuals were computed for the 50ms rise time stimuli and the 15ms intensity-matched stimuli when presented as frequently occurring standards. Visual inspection of these grand averages showed the maximal N1 response to be at a fronto-central location, specifically at electrodes F3, Fz and F4. Figure A5 shows the grand average waveforms for each rise time at these electrode sites.

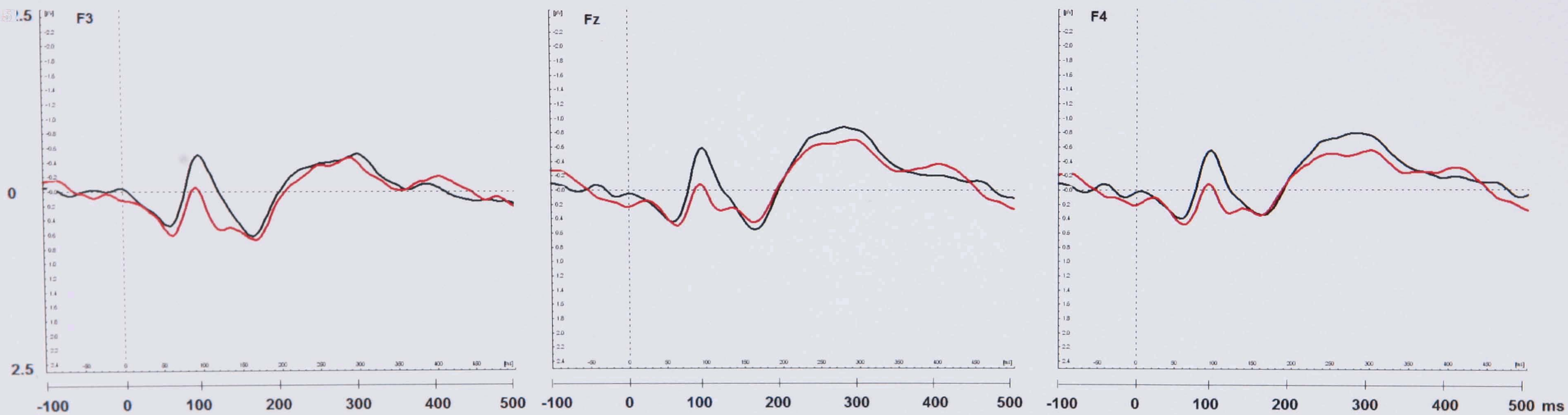
At all three electrode sites a difference in N1 amplitude can be seen between the two standard types at 75-150ms post-stimulus onset, with a greater amplitude observable for the shorter 15ms rise time stimuli. The statistical significance of this N1 amplitude difference was tested using Wilcoxon Paired Rank Tests. These analysis found statistically significant differences in N1 amplitude for the respective rise time stimuli at all three electrode sites (F3, Wilcoxon $Z = -2.70$, $p<0.01$; Fz, Wilcoxon $Z = -2.67$, $p<.01$; F4, Wilcoxon $Z = -2.76$, $p<.01$). There were no significant differences in N1 latency between contrasting rise time standards.

Summary of Experiment 2 findings

Experiment 2 confirmed that even with overall stimulus intensity controlled between standard and deviant stimuli, rise time variation elicits differentiated N1 responses in healthy adult listeners.

A5 Grand average waveforms for N1 responses to 15ms (IM) and 50ms rise time stimuli.

15ms IM rise time 50ms rise time



sophisticated study in which sinewave speech analogue stimuli were used, which could be perceived as either speech or non-speech depending upon how they were introduced to the listener. The stimuli were then presented in both a categorical perception paradigm as well as a discrimination task. The authors found that for both the speech and non-speech conditions, the dyslexics were *better* than controls at discriminating acoustic differences between stimuli from within the same category. In terms of categorical perception, the dyslexic children were less categorical than average readers in the speech condition, though differences were less clear cut in the non-speech condition. Taken together, the authors concluded from these findings that the perceptual difficulty evinced by dyslexics could not be an exclusive difficulty with formant transitions, since performance differences were elicited between stimuli identical in their formant and general acoustic structure; the only difference was the linguistic context. Semiclaes et al. took this as evidence of a speech-specific processing deficit. A more recent study by Blomert and Mitterer (2004) using similar speech and non-speech continua found the opposite results however, with dyslexic children manifesting more normal categorisation judgements for the non-speech stimuli. The generalisability of dyslexics' auditory processing deficits across speech and non-speech thus remains uncertain.

4.2.4 Challenges to the RAPD Hypothesis III: Supra-segmental auditory processing deficits in dyslexia

Sections 4.2.2 and 4.2.3 have questioned whether the auditory deficit in dyslexia is specific to rapid acoustic transitions, whilst no study has yet convincingly linked observed non-speech perceptual deficits to their purported speech equivalents.

One possibility is that the current failure to find a common auditory processing deficit with sufficient theoretical and empirical power is a result of the fact that auditory processing deficits are neither necessary nor sufficient in explaining the core phonological deficits of dyslexia. Such an argument has been put forward and in a quite comprehensive review of the literature, Ramus (2003), for example, estimated that once one goes beyond group means the actual reported incidence of auditory