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### DOCTOR OF PHILOSOPHY

#### The role of phonological processing and attention in developmental dyslexia: an eventrelated potential investigation

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# The Role of Phonological Processing and Attention in

### Developmental Dyslexia:

### An Event-Related Potential Investigation

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The thesis is submitted in part fulfilment of the degree of Doctor of Philosophy, completed at the Centre for Cognitive Neuroscience, School of Psychology, University of Wales, Bangor.



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## Abbreviations

ADD	Attention Deficit Disorder
ADHD	Attention Deficit Hyperactivity Disorder
AEP	Auditory Evoked Potential
EEG	Electroencephalography
ERP	Event-related Potential
IQ	Intelligence Quotient
ISI	Inter-stimulus Interval
MC	Magnocellular
MMN	Mismatch Negativity
PC	Parvocellular
RAN	Rapid Automatized Naming
RT	Reaction Time
SOA	Stimulus onset Asynchrony
VEP	Visual Evoked Potential
VOT	Voice Onset Time

### Abstract

Developmental dyslexia is characterised by poor reading and spelling skills affecting up to twenty percent of English children and adults (Habib, 2000). Phonological deficits have been proposed to be a core feature of dyslexia (Snowling, 2000). Here we used event-related potentials (ERPs) to examine neurophysiological correlates of phonological processing in dyslexic adults. We found that, unlike controls, dyslexic adults engaged in a lexical decision task fail to shift their attention to phonological variations within a stream of alliterated words. However, when phonological deviants are made task-relevant, no differences between dyslexic adults and controls are found, even for minimal pairs (e.g., /b/ - /p/). The first result is consistent with a phonological deficit in developmental dyslexia, but the latter suggests an important role of attention. Therefore, we subsequently used a phoneme deletion task in which phonological deviants remained task-relevant but attentional demands were increased. In such conditions, the phonological deficit, characterized by significantly reduced P3 ERP amplitudes, reappeared in dyslexic adults. To test the verbal specificity of this effect, we then compared phoneme and pure tone deletion: In both tasks dyslexic participants showed a P3b amplitude reduction, which correlated with reading and spelling performance. Finally, we tested whether the attentional deficit generalizes to the visual modality using a nonverbal oddball paradigm in which participants had to detect targets differing from the standards in one dimension (pitch or volume for tones; form or contrast for shape) or two dimensions simultaneously. Contrary to our predictions, we found reduced P3b amplitudes in dyslexic adults for stimulus changes

in one but not two dimensions. The findings are discussed in relation to compensation strategies and ADHD co-morbidity. Overall, our results suggest the existence of an attention capacity deficit in developmental dyslexia, which may interact with phonological processing but is not specific to verbal material. ... word recognition [in reading] is the product of orchestrated activity that occurs within a number of cognitive sub-systems... (Ellis, 1993, p.24)

### Chapter 1

# Cognitive Processes Fundamental to Reading and Reading Development

Upon entering primary school at around 5 years old most children are already competent users of spoken language. They have acquired speech comprehension and production abilities over a relatively short period of time with what is generally agreed to be very limited instruction. In comparison, the development of reading skill is much more variable being acquired slowly after extensive formal instruction (Gleitman & Rozin, 1977).

Text is essentially a visual analogue of speech; once converted into a suitable form, written words can be processed in the same way as spoken words. However the conversion of visual words into a comprehendible auditory form is not a simple process and requires the interaction of several different cognitive processes (Ellis, 1993). This interactive network of cognitive sub-systems takes time and training to develop from established spoken comprehension and production networks.

#### 1.1 A Model of Fluent Single-word Reading

At the most basic level reading requires the visual discrimination of words, the conversion of these words into some appropriate abstract representation and the

holding of this representation in working memory while searching for a matched lexical form in memory. In order to accomplish this process models of fluent singleword reading propose three main cognitive systems of representation are involved: Phonological, orthographic and lexical-semantic. However, current models differ with respect to how they propose these systems interact.

Phonological processes concern the mappings of meaning to the established spoken representations of words. Orthographic processes concern the relationship between visual letters and phonemes which are not always consistent in a language like English (e.g. while the 'g' in gate is pronounced /g/, the 'g' in general is pronounced /dʒ/). Finally, lexical-semantic processes link the phonological and orthographic decoding processes to the meanings of words.

One influential model of single-word reading proposes two mechanisms (routes) by which the pronunciation of words can be gained (dual route model, see Figure 1.1; Coltheart, 1993). One route retrieves the phonological structure of whole words from their written representation using a lexicon of learned words. This is often referred to as the lexical route and is believed to be essential for the correct pronunciation of irregular words (e.g. yacht). The second route is an active decoding process whereby letters are converted into sounds according to general graphemephoneme correspondence rules.

According to the dual route model, regular words are accurately pronounced using either route. However, irregular words are more accurately read using the lexical route and pseudo-words using the sub-lexical route. Nevertheless, individual differences in word reading errors between adults, suggest that route selection is not automatically directed for regular, irregular and pseudo-words (Rastle & Coltheart, 1999a; 1999b). Furthermore, in some cases individuals show seemingly strategic

tendencies towards the use of one route over the other, irrelevant of regularity (e.g. Baron & Strawson, 1976).



Figure 1.1 - Simplified dual-route model of single-word reading.

Pennington (1999) suggests that the dual route model underestimates the role of phonological processing in reading. For one, non-word reading performance and irregular word reading performance are highly correlated, which would not be expected for if they are controlled by two independent routes (Gough & Walsh, 1991). Furthermore, many reading studies suggest that phonological representations of words are activated automatically in the process of semantic access (see Van Orden, Pennington, & Stone, 1990). For example Van Orden (1987) found that homophones primed semantic categories (e.g. ROWS primed flower). Overall the dual route model discriminates lexical and sub-lexical phonological processing, whether or not semantic access can be independent of phonological processing.

#### 1.2 A Model of Single-word Reading Development

In fluent adult readers interactions between the cognitive sub-systems required for reading are relatively automatic, requiring very little attention by the reader. However, developing readers are less skilled and need to apply much more effort to the smooth interaction of these cognitive systems (Rayner & Pollatsek, 1989).

Studies of reading development suggest that children progress through the use of a series of strategies before reaching a fluent reading system (Chall, 1983; Ehri, 1991; Frith, 1985). Ultimately the aim of these strategies is to build associations between print and meaning that can be used to comprehend text. This is accomplished by both the building of new phonological and orthographic language associations and the strengthening of already existing phonological and semantic associations for spoken comprehension and production.

In the initial stages of reading development, children focus on the salient characteristics of whole-words as graphic symbols (logographic phase; Frith, 1985). Clearly sufficient visual discrimination abilities need to have developed before word recognition can be established. During this phase of development, visual input dominates the reading process, playing a basic but crucial role in the perception of words. Consequently, salient contextual cues (e.g. font and colour) have a large impact on the words children can read. Classically children at this stage will correctly read words in a familiar (logo) context, but misread whole words placed in an unknown context and fail to notice changes in letters for words in a familiar context, e.g. xepsi for pepsi (Masonheimer, Drum, & Ehri, 1984). At this stage of reading development it is parsimonious to hypothesise that the same processes used for object recognition are also used in the processing of words (see Figure 1.2; Ramus, 2004).

Also evident in the model of logographic reading is the presence of sub-lexical phonological representations which are developed as part of the speech perception system in infancy, and lexical phonological processes which develop during spoken vocabulary acquisition (Ramus, 2004).



Figure 1.2 – A model of the processes involved during the logographic stage of reading development. Adapted from Ramus (2004).

Beyond a logographic strategy, reading requires the identification of individual letters. Letters of the English (Indo-European) alphabet can be reduced to a limited set of strokes differentiated by trajectory, orientation and mirror image. While helping to maintain a simple and replicable alphabet, these symbols also place pressure on the accuracy of the visual system. Although reading the mirror reversal of letters (e.g. p instead of b) is anecdotally reported to be common in beginning readers, experimental evidence suggests that this is not the case ( Liberman, Shankweiler, Orlando, Harris, & Bell-Berti, 1971; however for evidence in dyslexic readers see Terepocki, Kruk, & Willows, 2002). Isolated geometric discrimination abilities are fully developed prior to beginning reading, and further training in non-verbal geometric discriminations seems to have little effect upon reading performance (Stevenson, 1976). However, general image reversal problems extending to left-right body confusion as well as letter reversals seem to be more prevalent in children with poor spoken language skills (i.e. these deficits are not specific to reading difficulties McMonnies, 1992).

In an alphabetic writing system like English the use of a logographic reading strategy fails to take advantage of general rules for the pronunciation of words. However, with the realization of the abstract letter-sounds correspondences that exist in English, children begin to decode words in an analytic manner (U Frith, 1985). Classically in this stage of development children's reading is marked by non-word errors resulting from the inappropriate use of a phonological recoding strategy, rather than the visually similar word errors made during the logographic stage (Barr, 1972; Cohen, 1974/1975; Elder, 1971).

During the transition from the logographic phase to the alphabetic phase, an awareness of letter identification and letter position is established. At this stage attention becomes focused on individual letters (Ehri, 1991). In order to read words independent of style, font, colour and size, letters must be represented in an abstract form (Coltheart, Patterson, & Marshall, 1980; Polk & Farah, 1997). Furthermore in order to dissociate words that are differentiated by letter order (e.g. STAGE and

GATES; SALT and SLAT) letter order must be represented (Caramazza & Hillis, 1990).

The development of an alphabetic reading strategy signals more than a change in the size of the units of visual word representation (letters instead of whole-words). Learning simple associations between letters and sounds is not sufficient to develop accurate decoding skills. Instead, a child must develop associations between letters and the specific phonemic units of spoken language. It is these phonological associations that will establish a link between the visual word form and word meaning (see Figure 1.3).



Figure 1.3 – A model of the processes involved during the alphabetic stage of reading development. Adapted from Ramus (2004).

Here it is important to note that phonemes are not discrete invariant units, but variable acoustic signals that differ with every pronunciation, even by the same speaker (McMahon, 2002). Furthermore, the phonemes contained in words are affected by each other, blending together into coherent acoustic units. While phonemes like /b/ have essentially very little sound without the pronunciation of a subsequent vowel, /b/ is clearly represented in the language system independent of a vowel, as /b/ can be identified, isolated, removed and added to other words. It is this awareness of phonemic units that characterizes the alphabetic stage of reading development.

The development of decoding skill enables the reading of unfamiliar words without the need to hear the spoken form of the word first. Once children start to develop their decoding skills their ability to read unfamiliar, but regular words is greatly improved (Carnine, 1977). However, these decoding skills are of little use in the reading of irregular words (e.g. yacht).

In the final phase of reading development children acquire orthographic skills (Ehri, 1991; Frith, 1985). This stage of development is characterized by faster and more fluent reading. Although focused on visual representations like the logographic strategy, unlike the logographic strategy the orthographic strategy is an analytical process. Orthographic knowledge increases with experience as the phonological structure of words draw attention to similarities in their letter representations (Marsh, Friedman, Welch, & Desberg, 1981; Massaro, Taylor, Venezky, Jastrzembski, & Lucas, 1980). However, some evidence suggests that orthographic analogies are used by very young readers to strengthen phonological decoding and therefore facilitate the formation of an alphabetic strategy (Goswami & Bryant, 1990). Either way, the

frequent recognition of letter patterns across words results in the formation of orthographic lexical representations (See Figure 1.4; Ehri, 1991; Ramus, 2004)



Figure 1.4 – A model of the processes involved during the orthographic stage of reading development. Adapted from Ramus (2004).

#### **1.2.1 Phonological Awareness**

The acquisition of a store of sub-lexical phonological representations starts prior to experience of reading. Specifically, infants as young as 6-months old are capable of discriminating between syllables varying only in voicing (e.g. /ba/ and /pa/ Eimas, Siqueland, Jusczyk, & Vigorito, 1971; Jusczyk, 1994). However, in contrast to simple discrimination of sub-lexical phonological cues, the acquisition of reading requires 'explicit' knowledge about the sound structure of words (Gleitman & Rozin, 1977; Liberman, 1973; Rozin, 1976; 1978; Rozin & Gleitman, 1977). This knowledge has been termed phonological awareness and is not a requisite of speech comprehension or production (Liberman, 1973). Essentially phonological awareness is the ability to distinguish and manipulate the unit sounds of language: syllables, onsets, rimes and phonemes (Yopp, 1988).

Phonological awareness proficiency can be characterized by sensitivity (weak or strong, according to the task requirements, see Table 1.2) and by the size of phonological units (large or small, see Table 1.1). Importantly, phonological awareness develops from the representation of large units in young children and small units in adults (Anthony, Lonigan, Driscoll, Phillips, & Burgess, 2003). Awareness of relatively large phonological units (i.e., words or syllables) is found in pre-literate children (Liberman, Shankweiler, Fischer, & Carter, 1974; MacLean, Bryant, & Bradley, 1987) and illiterate adults (Morais, Bertelson, Cary, & Alegria, 1986). Therefore onset-rime and phoneme units seem to be the most important for reading development.

Level	Example Segmentation	
Word	PLANET	/plæn I t/
Syllable	PLA-NET	/plæ-nɪt/
Onset-rime	PL-ANET	/pl-ænīt/
Phoneme	P-L-A-N-E-T	/p-1-æ-n-I-t/

Table 1.1 – Levels of phonological representation.

Task	Processes Involved	Example Studies
Oddity Task	Segmentation,	Ackerman et al., 1990
Spot the odd-one-out in a	Discrimination, STM.	Bradley & Bryant, 1978
phonologically similar		
series of words, e.g. cot,		
cat, <i>dot</i> .		
Phoneme Deletion	Segmentation,	Bruce, 1964
Repeat a word with its	Articulation, STM.	Bruck & Treiman, 1990
first phoneme removed,		Fawcett & Nicolson, 1995
e.g. brain – <i>rain</i> .		
Spoonerism	Segmentation,	Perin, 1983
Repeat a pair of words	Articulation, Working	Landerl & Wimmer, 2000
with their first phonemes	Memory <sup>1</sup> .	
swapped, e.g. car park –		
par cark.		
Pig Latin	Segmentation,	Pennington et al., 1990
Repeat a word with its	Articulation, Working	
onset moved to the end of	Memory.	
the word and 'ay' added,		
e.g. brain – <i>ainbray</i> .		

<sup>&</sup>lt;sup>1</sup> Although often used interchangeably, here STM has been used to describe a process of short-term storage (rehearsal) and recall, whereas Working Memory has been used to describe a process which requires the dynamic manipulation of items that also require rehearsal and subsequent recall (Baddeley, 1990).

Table 1.2 – The processes underlying different phonological awareness tasks. Although the phoneme awareness tasks identified in Table 1.2 vary in their general cognitive demands they load heavily on the same cognitive process when phonological unit size is controlled for (Stahl & Murray, 1994).

In summary, phonological processes are fundamental to the development of reading. Specifically, poor phoneme awareness is likely to detriment the acquisition of the alphabetic principle, preventing the development of connections for sub-lexical phonological processes (Frith, 1985).

[Developmental dyslexia is] *A disorder manifested by difficulty in learning to read despite conventional instruction, adequate intelligence, and socio-cultural opportunity. It is dependent upon fundamental cognitive abilities which are frequently of constitutional origin.* (Critchley, 1970, p.11)

### Chapter 2

#### **Developmental Dyslexia**

Literacy acquisition can be impaired for a number of extrinsic and intrinsic reasons (e.g. poor social interaction or low intellectual capacity). However, impaired reading and spelling characteristic of developmental dyslexia occurs in children and adults equipped with the necessary intellectual abilities and having received sufficient literacy training. Even after receiving extensive remedial instruction these children show persistent difficulties in fluent reading and spelling (Torgesen et al., 2001). Furthermore, deficient reading and spelling remains even for highly compensated dyslexic adults (e.g. Hatcher, Snowling, & Griffiths, 2002).

Developmental dyslexia has been estimated to affect between 4 and 20 percent of English speakers (Démonet, Taylor, & Chaix, 2004; Habib, 2000; Rutter & Yule, 1975; Shaywitz et al., 1999). However, these estimates are inflated by differences in the criteria used to diagnose dyslexia (Snowling, 2000). More conservative estimates have suggested up to 10 percent of school age children from a range of socialeconomic backgrounds and with different levels of general cognitive ability are developmentally dyslexic (Badian, 1993; Stein, 2001). Diagnosed cases of dyslexia rarely present with the same symptoms. In addition to reading and spelling problems; left-right confusions, untidy handwriting, poor mathematics skills and difficulty remembering the order of short spoken sequences are just some of the many behavioural symptoms associated with dyslexia (Miles, 1993). However, whether all of these symptoms are associated purely with the presence of dyslexia or additional co-morbid developmental conditions is a matter of some debate.

The diagnosis of dyslexia has been based on a range of psychometric testing procedures. One difficulty for the diagnosis of dyslexia is whether dyslexic difficulties should be, or indeed can be, discriminated from general poor reading. Some studies suggest that two distinct populations of poor readers exist that are consistent with a biological developmental impairment on the one-hand and a lack of the social and general cognitive prerequisites for literacy development on the other (Ellis & Large, 1987; Rutter & Yule, 1975). However, other studies have failed to find any qualitative differences between poor readers, suggesting that dyslexia is a severe case of poor reading (Shaywitz, Fletcher, Holahan, & Shaywitz, 1992; Shaywitz, Escobar, Shaywitz, Fletcher, & Makuch, 1992). Currently assessments of dyslexia carried out in the UK diagnose dyslexic difficulties on the basis of a discrepancy between an individual's reading and spelling performance and that predicted by their IQ. Because IQ has been shown to correlate with reading performance it can be used as a predictive measure of expected reading performance (e.g. Rutter & Yule, 1975). However, diagnosis of dyslexic readers from poor readers on the basis of IQ dictates that only individuals with a relatively high IQ will be diagnosed as dyslexic (Siegel, 1992). As a biological syndrome dyslexia should be equally well represented in less intellectually developed children as well as those with

average intelligence. As Frith (1997; 1999) points out, these difficulties with diagnosis are likely to relate to measurement of impairments at the behavioural level and failure to examine deficits at the cognitive and biological levels. Importantly, at the cognitive level many studies have failed to find discrepancies in measures predictive of dyslexia between dyslexic and poor readers (Stanovich, 1991; Stanovich, Siegel, & Gottardo, 1997a, 1997b), suggesting that a discrimination between garden variety poor readers and dyslexic readers is not useful.

#### 2.1 Causal Theories

As discussed in Chapter 1, the development of reading requires the interaction of several cognitive sub-systems and their neural substrates. Impairments to one or more of these cognitive subsystems would create similar impairments in reading. In addition, some of the cognitive processes fundamental to reading are also essential to other behaviours. As such, impairments to these processes may be accompanied by difficulties that are not directly relevant to reading. Consequently, over the last 25 years several plausible causal theories of developmental dyslexia have been proposed.

#### 2.1.1 Phonological Theory

Phonological processes are essential to the development of reading English (Chapter 1). The phonological theory proposes impairment in phonological processes as the cause of the reading difficulties observed in dyslexia. Phonological processes are fundamental to a range of language skills not just learning to read. Consequently studies supporting the phonological theory have shown that dyslexic participants perform poorly in a wide range of speech and language tasks that require

phonological processes: Phonological awareness, speech perception, non-word reading, verbal short-term memory, and rapid automatised naming (RAN).

#### 2.1.1.4 Phonological Awareness Deficits

Poor readers and dyslexic individuals are impaired in performance on a range of phonological awareness tasks: Oddball detection (Ackerman, Dykman, & Gardner, 1990a; Bowey, Cain, & Ryan, 1992; Bradley & Bryant, 1978), phoneme deletion (M. Bruck & Treiman, 1990; de Gelder & Vroomen, 1991; Fawcett & Nicolson, 1995), spoonerisms (Cornelissen, Hansen, Hutton, Evangelinou, & Stein, 1998; Landerl, Wimmer, & Frith, 1997) and piglatin (Pennington, Van Orden, Smith, Green, & Haith, 1990).

Bradley and Bryant (1978) found that dyslexic children were impaired for the categorisation of an odd word based on its first phoneme in an alliterated set (e.g. bed, bag, red, bow). Furthermore, training in alliteration (segmentation) skills improved the later reading performance of a group of pre-readers compared with pre-readers trained in semantic categorisation (Bradley & Bryant, 1983).

#### 2.1.1.1 Speech Perception Deficits

Although dyslexic readers are clearly impaired for the identification of written words, they have little difficulty identifying spoken words (Brady, 1997; McBride-Chang, 1996). Therefore, if dyslexic children do have deficits in speech perception these deficits are subtle and may be better detected when phonological contrasts are masked by irrelevant noise. In one such study, Brady, Shankweiler & Mann (1983) found dyslexic children were poorer at discriminating CVC syllables in noise than control children. Speech discrimination deficits have also been observed in dyslexic adults for acoustically similar syllables not in noise (e.g., /pa/ and /fa/; (Adlard & Hazan, 1998; Cornelissen, Hansen, Bradley, & Stein, 1996). However the majority of evidence for a speech perception deficit in dyslexic adults and children comes from categorical perception tasks of synthetic speech stimuli (Brandt & Rosen, 1980; Godfrey, Syrdal-Lasky, Millay, & Knox, 1981; Manis et al., 1997; Masterson, Hazan, & Wijayatilake, 1995; Ruff, Marie, Celsis, Cardebat, & Démonet, 2003; Steffens, Eilers, Gross-Glenn, & Jallad, 1992; Werker & Tees, 1987).

At birth infants can discriminate a range of phonetic contrasts that exist across languages, but many of which do not exist in the infant's linguistic environment. As an infant develops these perceivable contrasts are reduced and phonological discriminations are limited to those present in the infant's linguistic environment (see Vihman, 1996 for a review}. These changes result in phonological contrasts of a specific language being perceived categorically. For example, increasing the voice onset time (VOT) of /ba/ along an artificial continuum will eventually lead to the perception of /pa/. In normal adults the change between the identification of a /ba/ versus a /pa/ is sharp, with no perception of an intermediate sounding syllable. This is termed categorical perception.

Brandt and Rosen (1980) failed to find any differences in the discrimination of synthetic CV syllables differing in VOT or place of articulation in dyslexic adults compared with controls. However, flatter discrimination functions for the dyslexic participants were indicative of reduced categorical perception compared with controls. Godfrey *et al.* (Godfrey, Syrdal-Lasky, Millay, & Knox, 1981) found similarly impaired discrimination functions in dyslexic participants as Brandt and Rosen (1980). In addition, Godfrey *et al.* (1981) found that dyslexic participants were less consistent in their categorisations of /ba/ - /da/ and /da/ - /ga/ syllables. Other studies

have also shown that dyslexic children and adults have less sharply defined categorical perception than controls (Steffens, Eilers, Gross-Glenn, & Jallad, 1992; Werker & Tees, 1987).

Masterson, Hazan and Wijayatilake (1995) found clear categorical perception deficits for a subset of dyslexic readers who were also poor in non-word reading. Manis, McBride-Chang and Seidenberg *et al.* (1997) identified a similar subgroup of dyslexic participants with flatter phoneme discrimination functions than controls. However, the presence of phoneme discrimination deficits was not related to phoneme awareness skills, suggesting that these deficits are independent. Importantly, deficits in categorical perception in dyslexic participants suggest impairments in between category discriminations, but not within category (allophonic) discriminations (i.e. phonetic discriminations that are irrelevant to phoneme recognition in a specific language, Serniclaes & Sprenger-Charolles, 2003). Indeed, dyslexic individuals may be more disposed to the discrimination of allophonic variations than controls (Serniclaes, Sprenger-Charolles, Carre, & Démonet, 2001).

#### 2.1.1.2 Non-word Reading Deficits

Normal reading performance is affected not only by decoding skill, but the top-down influences of lexical access. Therefore, the assessment of reading skill using high-frequency words gives no indication of the relative importance of decoding skill to reading performance. However, the reading of non-words that conform to the regularities of real word spellings (also referred to as pseudo-words) allows for the examination of decoding skill independent of lexical phonological representations.

Several studies have shown that dyslexic children and adults have particular difficulty in the reading of non-words (see Rack, Snowling, & Olson, 1992 for a

review). Furthermore, these difficulties have been shown to persist into adulthood, despite improvements in real word reading (e.g. Bruck, 1990). One plausible explanation for the non-word reading deficits observed in dyslexic individuals is that dyslexic children and adults have a verbal production impairment which is more observable in the reading of non-words, where locating a lexical representation can not scaffold word selection in the same way as real-word reading. Consistent with this, Snowling (1981) showed that dyslexic children were poorer at repeating relatively long non-words than controls. However, even when the effect of production is removed, dyslexic children are poor at matching spoken non-words to their written counterparts (Snowling, 1980).

Importantly, non-word reading has been shown to increase with reading performance in normally developing children, while dyslexic children show little improvement in non-word reading performance, despite improvements in real word reading (Snowling, 1980). Based on these findings, Snowling (1980) argues that there is a clear dissociation in the reading strategies implemented by normally developing readers and dyslexic children. While decoding skills are important to the reading performance of normally developing readers, they seem less important for dyslexic readers who are likely to develop a sight-word vocabulary independent of their decoding skills.

Not all studies have observed poor performance in dyslexic children on nonword reading tasks (Beech & Harding, 1984; Johnston, 1982; Treiman & Hirsh-Pasek, 1985). Although small sample sizes and differences in diagnostic criteria of the dyslexic samples examined are able to explain the failure to find effects in many of these studies, this is not the case for all of them (Vellutino & Scanlon, 1987).

#### 2.1.1.3 Verbal Short-term Memory

The majority of evidence suggests that verbal material is rehearsed and recalled in a phonological code. Because of this the phonological similarity and length of a set of words affects how well they are recalled (Conrad, 1964; Hulme, 1984). Furthermore, since short-term memory capacity is limited, faster speech rates are indicative of faster rehearsal leading to greater storage and recall (Hulme, Thomson, Muir, & Lawrence, 1984).

Verbal short-term memory is classically measured in tasks of remembering words, non-words or digits, all of which dyslexic children and adults are poor at (e.g. Ackerman, Dykman, & Gardner, 1990b; e.g. Plaza, Cohen, & Chevrie-Muller, 2002; Vargo, Grosser, & Spafford, 1995). Although some of these effects may be confounded by the presence of language comprehension impairments (e.g. specific language impairment, SLI) in participants (Baddeley & Wilson, 1993), even strictly classified dyslexic populations with good language comprehension skills show deficits in the recall of serial digit order (Helland & Asbjornsen, 2004).

Despite normal performance in tasks of non-verbal visual memory (e.g. Corsi Blocks task, Gould & Glencross, 1990), dyslexic children recall fewer words than age-matched controls, but the same as younger children with similar reading ability (Hulme, 1981; Johnston, Rugg, & Scott, 1987; Shankweiler, Liberman, Mark, Fowler, & Fischer, 1979). However, this deficit is not completely consistent with a developmental delay, as poor digit span is also observable in dyslexic adults (Hatcher & Hulme, 1999).

In respect to memorizing word lists, long-term lexical representations are beneficial to recall. Consequentially, high frequency words are recalled better than low frequency words, which are both recalled better than non-words (Hulme et al.,

1997). Impaired recall for words is therefore indicative of a deficit in phonological lexical representations, whereas poor recall of digit sequences is unlikely to be the result of impaired lexical representations, since the digits zero to nine are such frequently used words. Instead, poor performance in digit span tasks is likely to be the result of slower speech rates observed in dyslexic readers that result in inadequate rehearsal and subsequently poor recall (McDougall, Hulme, Ellis, & Monk, 1994).

#### 2.1.1.5 Rapid Automatised Naming Deficits

In fluent adult readers naming is a relatively automatic process. For well known items, lexical access is rapid and naming responses can be given very fast. However, dyslexic children and adults fail to show the same level of fluency (Felton & Wood, 1989; Wolf, 1986). In there seminal studies of rapid automatised naming (RAN) Denckla and Rudel (1976a; 1976b) showed that dyslexic children were slower at naming letters, digits and even coloured squares than controls. Since no phonological decoding is required for the identification of coloured squares for example, this impairment has been argued to be the result of slow skill automatisation which extends into reading (Wolf & Bowers, 1999). However, since naming does require access to the lexical phonological representations of words, a deficiency in these representations may significantly impair the naming speed of an object, including colours (Snowling & Hulme, 1994).

Although phonological processes are involved in all of the deficits discussed here, the relationship between them is unclear. Arguably all of these deficits could result from poor phonological representations, but conversely, poor phonological representations could conceivably result from several of these difficulties (e.g., speech perception or verbal short-term memory, see Figure 2.1). Therefore, studies of the phonological deficit still need to examine the specifics of the phonological processing deficits observed in dyslexic children and adults (Ramus, 2001).



Figure 2.1 - Plausible causal links between phonological processing deficits.

#### 2.1.2 Temporal Processing Theory

The temporal processing theory postulates an auditory perceptual basis for the observed phonological processing difficulties of dyslexic children and adults (Tallal, 1984). Current interpretations of the temporal processing theory propose an amodal timing deficit, although deficiencies in visual processes are regarded by some researchers as incidental and not causal to reading difficulties (Tallal, 1980). In contrast, other researchers have proposed that temporal visual deficits are also responsible for impaired reading accuracy and fluency in dyslexia (see Magnocellular Theory, this chapter).

A variety of experimental manipulations have been used to assess the temporal processing abilities of dyslexic children and adults. Often these tasks vary both in the type of response and level of discrimination and working memory ability they require. Tasks requiring judgments to made on a single stimulus, either alone or compared with a test stimulus, include the detection of a rapid onsetting stimuli, duration changes and changes in location. In these types of tasks dyslexic children show no evidence of impairment in single item identification at durations as low as 17 ms for visually presented single letters (Klein, Berry, Briand, D'Entremont, & Farmer, 1990) and 75 ms for complex tones (Tallal, 1980). However, judgements involving the order of rapidly presented successive stimuli (temporal order judgment, TOJ) are impaired in dyslexic participants (see Tallal, Miller, Jenkins, & Mezernich, 1997; Farmer & Klein, 1995 for reviews). Importantly, a recent study by Hood and Conlon (2004) showed visual and auditory TOJ performance in an unselected sample of pre-school children predicted later word reading accuracy and fluency, even after effects of general cognitive performance (i.e. digit span, inattention and non-verbal IQ) were accounted for.

#### 2.1.2.1 Auditory Temporal Processing

Tallal (1980) found dyslexic children were impaired for temporal order judgements made on pairs of rapidly presented tones (with small ISIs), but performed similar to controls on TOJ tasks with large ISIs. Furthermore, TOJ performance correlated strongly (r = .81) with non-word reading. In another task, Tallal (1980) found that dyslexic participants were also impaired for the same-different discrimination of tones separated by small ISIs up to 305 ms, but not for tones separated with ISIs of 428 ms. Tallal (1980) hypothesised that a deficit in temporal processing would impair the discrimination of phonemes, some of which (e.g. stop consonants) are discriminated primarily be spectral changes occurring in the first 40 ms (Liberman, Cooper, Shankweiler, & Studdert-Kennedy, 1967; Phillips & Farmer, 1990). Tallal (1980) suggested further that by impairing phoneme discrimination, temporal processing deficits may explain the phonological processing deficits found in dyslexia. Reed (1989) found dyslexic children were poorer than controls at samedifferent categorisations of synthesised stop consonant syllables and briefly presented tones, but not steady state vowels. These results, along with others, support Tallal's hypothesis that speech perception deficits in dyslexic individuals may be caused by an underlying deficit in processing brief auditory cues (De Weirdt, 1988). However, deficits in dyslexic participants for same-different judgements may be result of specific speech discrimination deficits rather than deficits in TOJ (Mody, Studdert-Kennedy, & Brady, 1997). Mody, Studdert-Kennedy and Brady (1997) confirmed TOJ deficits in dyslexic participants for acoustically similar syllables (e.g. /ba/ - /da/) at low ISIs. However, they failed to find these differences for TOJs of acoustically different syllables (/ba/ - /sa/) at the same ISIs. Furthermore, Mody, Studdert-Kennedy and Brady (1997) failed to find differences in TOJ for complex sine waves matched to the frequency changes of the second and third formants that characterise the acoustic differences between /ba/ and /da/, between dyslexic and control participants.

Not all studies of auditory TOJ have found differences between dyslexic and control participants (Nittrouer, 1999). Some studies have found poorer TOJ performance for poor readers compared with controls for relatively short compared with relatively long ISIs (Bretherton & Holmes, 2003; Cestnick, 2001; Cestnick & Jerger, 2000; Waber et al., 2001).

Many of these studies have failed to control for the large overlap of developmental dyslexia with ADHD (estimated at between 30 % and 70 %) and SLI (estimated at around 50 %, Fletcher, Shaywitz, & Shaywitz, 1999; McArthur, Hogben, Edwards, Heath, & Mengler, 2000). When controlling the presence of ADHD Waber, Weiler, Wolff *et al.* (2001) found TOJ deficits in dyslexic participants

compared with controls for speech and non-speech stimuli across all ISIs tested (10, 50, 100 and 400 ms). Similarly, Breier, Gray, Fletcher, *et al.* (Breier, Gray, Fletcher, Foorman, & Klaas, 2002) found TOJ deficits in dyslexic children without ADHD or spoken language deficits across short and long ISIs. However, these deficits were greater for speech stimuli in which performance correlated with independent measures of phonological processing. These results suggest that both concomitant attention and spoken language skills in dyslexic individuals affect performance on TOJ tasks. In dyslexic participants without these co-morbid conditions TOJ deficits are restricted to speech stimuli and may therefore by the result of poor speech discrimination deficits (Heath, Hogben, & Clark, 1999; Mody, Studdert-Kennedy, & Brady, 1997).

#### 2.1.2.2 Visual Temporal Processing

In a visual TOJ task Brannan & Williams (1988) found dyslexic participants were poorer at identifying the location of words and symbols appearing to the right or left of a central fixation. On average, dyslexic readers required a 20 ms longer SOA between stimulus presentations to perform as well as controls. In a similar task using words, May, Williams and Dunlap (1988) found that dyslexic children required greater SOAs than controls between stimuli when they were required to identify the words presented as well as when they only had to identity the location of the first stimulus. Importantly, TOJ performance was not affected by side of presentation and is therefore unlikely to be the result of a visual-spatial processing deficit (e.g.Hari, Renvall, & Tanskanen, 2001). Furthermore, deficits in visual TOJ judgement in dyslexic participants are not limited to complex visual stimuli, but have also been shown for brief light flashes (Kinsbourne, Rupo, Gamzu, Palmer, & Berliner, 1991). However, not all studies have found a TOJ deficit in dyslexic participants for visual

stimuli. Reed (1989) failed to find any differences between dyslexic and control participants for the TOJ of two symbols with ISIs between 50 and 400 ms.

### 2.1.3 Magnocellular Theory

The hypothesis of a deficit in the magnocellular system of the brain proposes a distinct neurophysiological basis of the temporal processing deficits observed in dyslexic children and adults. It also explains the lack of difference in visual acuity between dyslexic children and controls, while still proposing a visual deficit as the cause of the observed reading and spelling difficulties. Since its conception, the magnocellular theory has been extended to incorporate rapid auditory processing deficits also observed in studies of temporal processing (see Temporal Processing Theory, this chapter and Stein & Walsh, 1997).

The magnocellular theory is based on a deficit in the magnocellular pathway of the visual system. Two major channels are present in the visual pathway projecting from the retina of the eye to the visual cortex. One channel is suited to the processing of rapid low luminance stimuli (magnocellular, MC pathway) and forms a network predominately in the dorsal stream, the other is better suited to the processing of static high luminance and coloured stimuli (parvocellular, PC pathway) and predominately constitutes the ventral stream (Beaton, 2004). The different receptive properties of the MC and PC systems result in 'predominate' activation of one of these pathways under different environmental conditions (see Table 2.1).

Parvocellular System	Magnocellular System
High spatial frequencies	Low spatial frequencies
Low temporal frequencies	High temporal frequencies
(static)	(transient)
High luminance contrast	low luminance contrast

Table 2.1 - Receptive field properties of the parvocellular and magnocellular pathways.

Anecdotally, dyslexic children are reported to make more visual discrimination errors in identifying similar letters than average readers. However, very few experimental studies have examined this. Terepocki, Kruk and Willows (2002) examined the production and detection of letter reversals (e.g. b for d) in dyslexic children and found more production errors and poorer detection of letter reversals, compared with control children. Importantly, a series of studies performed by Chase, Ashourzaheh, Kelly *et al.* (2003) suggest that the MC pathway is dominant in visual aspects of reading.

Physiological evidence for the presence of a magnocellular deficit in dyslexic individuals comes from histological studies showing smaller cells in the magnocellular layers of the lateral geniculate nucleus (LGN) in dyslexic participants compared with controls, but not in the parvocellular layers (e.g. Livingstone, Rosen, & Drislane, 1991). Furthermore, cortical regions also seem to be impaired. Jenner, Rosen and Galaburda (1999) found an asymmetry for larger neurons in the left hemisphere of primary visual cortex for control brains that was not observed in dyslexic brains.
## 2.1.3.1 Motion Perception

On the surface the visual systems involvement in reading may seem to be limited to the fine grained discrimination of visual features that form letters. However, the perception of a detailed unmoving image when reading is not a direct representation of the image received on the retina. During normal reading, rapid saccadic eye movements are made between brief periods of fixations on words. The perception of stationary words is the result of two main compensatory mechanisms. Firstly, image changes caused by involuntary eye movements occur only briefly resulting in blended images that are not perceived as moving. Secondly, feedback from these moving images on the retina is sent through the MC system to bring the eyes back to fixation (Stein, 2001). Motion perception is indicative of the performance of these self-adjusting visual mechanisms and has been shown to predict letter position encoding in adults (Cornelissen et al., 1998). Furthermore, reduced sensitivity to coherent motion has been found in dyslexic participants compared with controls (Cornelissen, Richardson, Mason, Fowler, & Stein, 1995; Everatt, Bradshaw, & Hibbard, 1999; Pammer & Wheatley, 2001; Solan, Hansen, Shelley-Tremblay, & Ficarra, 2003). Witton, Talcott, Hansen et al. (1998) found that poor motion perception in dyslexic participants correlated with poor sensitivity to dynamic (frequency modulated, FM) tones, also thought to predominately tax the magnocellular system. Furthermore, Witton, Talcott, Hansen et al. (1998) found sensitivity to FM tones and motion perception correlated with non-word reading performance in dyslexic and control participants. These results support the presence of a magnocellular deficit in dyslexia for auditory and visual stimuli.

The importance of dorsal stream activity and therefore magnocellular functioning to the perception of coherent motion is supported by neuropsychological

patient studies and neuroimaging data. Patients with dorsal lesions show motion coherence deficits (see Talcott, Hansen, Assoku, & Stein, 2000). However, poor motion perception observed in extremely low birth weight children does not correlate with the presence of brain injury or reading and spelling performance, suggesting that poor motion perception alone is insufficient to impair reading (Downie, Jakobson, Frisk, & Ushycky, 2003). More importantly, performance on a form recognition task defined by motion correlated with general non-verbal IQ measures (Downie, Jakobson, Frisk, & Ushycky, 2003). FMRI studies support the presence of a visual deficit in dyslexic adults specific to motion. Several studies have found reduced activity in the visual association cortices for dyslexic participants compared with controls to visual stimuli (Demb, Boynton, Best, & Heeger, 1998; Demb, Boynton, & Heeger, 1997). More importantly, Eden, VanMeter, Rumsey *et al.* (1996) found reduced activity in association visual cortices (V5/MT) in response to moving stimuli in dyslexic adults compared with controls, but no differences in primary visual cortices (V1/V2) for static stimuli.

Not all studies have found differences between dyslexic participants and controls on motion perception tasks. Kronbichler, Hutzler and Wimmer (2002) failed to show differences between dyslexic participants and controls on tests of coherent visual motion perception and illusionary sound movement perception..

Examining the effects of temporal and spatial frequency on the sensitivity of dyslexic individuals to motion, Talcott, Hansen, Assoku *et al.* (Talcott, Hansen, Assoku, & Stein, 2000) used random dot kinematograms of varying temporal and spatial frequencies. Talcott et al. found similar deficits in dyslexic participants reported in previous studies (reduced motion coherence), however they also found that these motion coherence deficits were improved with an increase in dot density

(higher-spatial frequency), but not an increase in duration. These results are not completely consistent with a MC deficit, but are better explained by a deficit in spatial sampling irrelevant of speed.

#### 2.1.3.2 Visual Search Performance

Dyslexic adults are impaired for identifying the correct location of briefly flashed objects (and visual search Buchholz & McKone, 2004; Graves, Frerichs, & Cook, 1999). Iles, Walsh and Richardson (2000) found that dyslexic participants impaired for serial visual search also had elevated motion coherence thresholds.

Buchholz *et al.* (2004) found dyslexic participants performed as well as controls on pop-out visual search, but were significantly impaired for performance on a conjunction visual search task as well as having lower contrast sensitivity thresholds indicative of a MC impairment. Although indicative of a MC deficit, these results are also consistent with a deficit in spatial cueing. By providing dyslexic and control participants' with spatial cues in a visual search task, Roach and Hogben (2004) found impairments in dyslexic participants for spatial cueing independent of visual search (for which they were unimpaired). Furthermore, Roach and Hogben (2004) failed to find any evidence of MC deficits in their participants. These results are consistent with the presence of an attention deficit in dyslexic individuals that is independent of MC deficits.

#### 2.1.3.1 Psychophysical Thresholds

Consistent with a deficit in MC function, dyslexic individuals are more sensitive to changes in luminance contrast than controls (Bednarek & Grabowska, 2002; Floyd, Dain, & Elliott, 2004). Furthermore, Bednarek *et al.* (2002) found that sensitivity to luminance contrasts correlated with reading and spelling performance in dyslexic children. Although it was not the case for the above studies, Skottun (2000) warns that changes in contrast alone are not enough to ensure selective activation of the MC system. Stimuli must also be presented at low spatial frequencies and high temporal frequencies, otherwise there is a risk of activating the PC system as well.

Sperling, Lu, Manis *et al.* (2003) examined shape detection thresholds in dyslexic children and controls for achromatic contrast stimuli (black and white) and isoluminant colour stimuli (red and green). The illusion of shape was created by counter-phase flickering dots. Dyslexic children had a lower detection threshold for the illusionary shapes composed of achromatic flickering dots than controls. However, detection thresholds did not differ between dyslexic and control participants for illusionary shapes composed of isoluminant colour flickering dots. Importantly, Sperling *et al.* (2003) found that achromatic shape detection thresholds positively correlated with irregular word reading performance and performance on an orthographic decision task (selecting the correct spelling of a word when it is matched with a pseudohomophone, e.g. soap and sope). However, achromatic shape detection thresholds negatively correlated with phonological skills (non-word reading and phoneme deletion). Overall, these results suggest that MC deficits are distinct from phonological processing deficits and may independently impact orthographic processes in dyslexic individuals.

The findings of several studies suggest that MC impairments are limited to only a subset of dyslexic participants. Amitay, Ben-Yehudah, Banai *et al.* (2002) showed impairments in MC function in only 20% of the dyslexic participants they tested. In addition, they found that many dyslexic participants were impaired for tasks predominately taxing the PC system. Some studies suggest that MC deficits are part

of a subtype of dyslexia (Borsting et al., 1996; Everatt, Bradshaw, & Hibbard, 1999). However, Williams, (Williams, Stuart, Castles, & McAnally, 2003) found no evidence of reduced visual contrast sensitivity for low spatial and high temporal frequency stimuli or high spatial and low temporal frequency stimuli in a range of dyslexic adults categorised according to three different subtypes (phonological, surface, mixed). Importantly, Barnard, Crewther & Crewther (1998) report developmental improvements in low contrast flickered letter identification up to 10 years olds, although no significant differences were found between poor readers<sup>2</sup> and controls. It follows that impaired MC deficits found in adolescent children and adults may be the result of a developmental delay, however this delay does not seem to affect reading performance.

### 2.1.4 Automaticity-Cerebellar Deficit

In addition to the characteristic reading and spellings difficulties observed in dyslexia, a wide range of deficits in motor dexterity, including reduced muscle tonus, posture control, co-ordination, balance and smooth eye pursuit have been reported in dyslexic children and adults (Black, Collins, De Roach, & Zubrick, 1984; Miles, 1993; Moe-Nilssen, Helbostad, Talcott, & Toennessen, 2003). However, findings of motor impairments are not universally found in dyslexic children and adults. Nicolson and Fawcett (1990) found that dyslexic children performed worse than controls on a series of balance tasks only when they were required to perform a concomitant cognitive task (i.e., counting backwards). Based on their results, Nicolson and Fawcett (1990) proposed that dyslexic symptoms including motor difficulties, could be

 $<sup>^2</sup>$  Identified as at least 1 year behind for 4 - 6 year age group and at least 2 years behind for the older age groups.

explained by a general impairment in skill automatization: "the process by which, after long practice, skills become so fluent that they no longer need conscious control" (Nicolson & Fawcett, 1994). Furthermore, they argue that these deficits are difficult to reconcile with theories that postulate dyslexia results from impairments limited to language function (Nicolson & Fawcett, 1990).

#### 2.1.4.1 Behavioural Evidence

The importance of automaticity in reading is evident from studies examining rapid naming responses and lexical interference paradigms, such as the Stroop task (Stroop, 1935). In normal adults and children, the identification of the coloured ink of a typed colour name (e.g. BLUE) is impeded (slower reaction times and greater errors) when the colour ink and colour name are incongruent (e.g. BLUE, Helland & Asbjornsen, 2000; Stroop, 1935). Interestingly, Helland and Asbjornsen (2000) report no such congruence effect in a sub-group of dyslexic children also presenting with impaired receptive language skills. Slower naming of common object pictures (rapid automatised naming, RAN) has also been reported for dyslexic children (Denckla & Rudel, 1976a, 1976b; Meyer, Wood, Hart, & Felton, 1998). Although suggestive of a general deficit in automatic processing, RAN deficits have also been interpreted as the result of impaired lexical representations (Murphy, Pollatsek, & Well, 1988), possibly at the level of phonology (Snowling & Hulme, 1994).

Studies showing the influence of the cerebellum in language functions as well as automatic motor processes, lead Nicolson and colleagues to propose a deficit in cerebellar function as the likely locus of automaticity impairments (Nicolson, Fawcett, & Dean, 2001). Under this hypothesis, motor impairments are not causal to

the reading and writing problems observed in dyslexia, but are an incidental consequence of a cerebellar dysfunction.

## 2.1.4.2 Neurophysiological and Neuroanatomical Evidence

Studies of morphological changes in dyslexic adults have reported widespread differences in the temporal, parietal and frontal lobes as well as the cerebellum (Brown et al., 2001; Eliez et al., 2000). Leonard, Eckert, Lombardino et al. (2001) report a significant leftward asymmetry of the anterior cerebellum in dyslexic participants with phonological deficits. Consistent with this, Eckert, Leonard, Richards et al. (2003) report the anterior cerebellar lobes to be reduced in dyslexic participants as compared with controls. Combined with a measure of the right pars triangularis, Eckert, Leonard, Richards et al. (2003) were able to correctly identify 72% of the dyslexic participants in their sample. Interestingly, 94% of these participants showed a deficit in RAN, and all these neurological measures correlated with reading and spelling measures as well as other language specific measures. Contrary to these findings, Rae, Harasty, Dzendrowskyj et al. (Rae et al., 2002) found a rightward cerebellar asymmetry in control participants that they did not find in dyslexic participants, whereas Eliez, Rumsey, Giedd et al. (Eliez et al., 2000) were unable to find any morphological differences in the cerebellum of the dyslexic participants in their study. Differences in the results of these studies may relate to the measures used to estimate tissue volume (Beaton, 2004; Beaton, 2002).

In addition to measuring structural changes, other studies have examined functional (metabolic) differences between dyslexic and control adults. Rae, Lee, Dixon *et al.* (1998) found metabolic differences in the ratio of choline-containing compounds (neurotransmitters) to N-acetylasparate in the right cerebellum and left

temporal-parietal region. They argue that these changes reflect differences in cell density. Consistent with this interpretation, Finch, Nicolson & Fawcett (2002) in analysis of cell size densities, found an increased proportion of large cells, but much fewer small cells in the cerebellum of dyslexic adults compared with controls.

Nicolson, Fawcett, Berry *et al.* (1999) examined the function of the cerebellum in dyslexic adults during a sequence learning and sequence execution task using PET, both tasks were selected as being functionally controlled by the cerebellum. Nicolson, Fawcett, Berry *et al.* (1999) found reduced activity of the right cerebellar cortex in both tasks for dyslexic participants compared with controls. Using a reading aloud and silent reading task, Brunswick, McCrory, Price *et al.* (1999) presented dyslexic participants with simple words and pseudowords at a pace in which the reading performance of dyslexic and control participants was equal. By removing the effect of fluency in this way and still examining the reading process, Brunswick *et al.* observed a reduction in activity in the left cerebellar (among other regions) for dyslexic adults compared with controls. This same reduction in activity was shown for the left cerebellar hemisphere when repeating words and pseudowords (McCrory, Frith, Brunswick, & Price, 2000).

The cerebellum is a structure located at the most posterior and ventral part of the brain; subtended from the brain stem it forms two cerebella (hemispheres) positioned either side of the fourth ventricle. Although a phylogenetically older part of the brain, a large body of recent research has shown it to be part of a complex network of cortical and sub-cortical processing (e.g., Leiner, Leiner, & Dow, 1991). Neuroimaging studies have shown activity of the cerebellum in language-related tasks and patients with cerebellum trauma also show language impairments (e.g., Ivry & Justus, 2001). Specifically patients with cerebellar vermis/paravermis lesions or

olivopontocerebellar atrophy make more reading and spelling errors than healthy controls (Moretti, Bava, Torre, Antonello, & Cazzato, 2002; Moretti et al., 2002) although it is important to note that the types of reading and spelling errors made by these patients are not the same as those made in cases of acquired or developmental dyslexia (Beaton, 2004).

Overall, although differences have been found in the cerebellum of dyslexic and control participants these are not independent of other diffuse cortical deficits (Beaton, 2002).

# Chapter 3

# **Event-related Potentials and Dyslexia**

Research into developmental dyslexia aims to elucidate the covert processes that underlie the reading and spelling difficulties experienced by a significant proportion of children and adults. A thorough understanding of how these processes differ in dyslexic and unimpaired individuals can support the devising of effective remediation and compensation programs. As all cognitive processes are fundamentally produced at the neural level, measuring brain activity is a promising approach to investigating the cognitive processes involved in reading.

## 3.1 Principles of Event-related Potentials

#### **3.1.1 Basic Principles**

Electroencephalography is a physiological measure of the resulting activity of neuron populations recorded over the scalp. It capitalises on the wide spread ion displacements that occur throughout the brain mass when neurons are active and result in global electric field variations over the scalp. In the pyramidial layers of the cortex in particular, the arrangement of neurons perpendicular to the scalp results in summed dipolar fields that can be measured as potential differences from its surface. An electroencephalogram plots the amplitude of the measured signal, normally ranging from -150 to  $+150\mu$ V, against time. The frequency of the signal can range anywhere from approximately 1 to 40Hz (Coles & Rugg, 1995).

Event-related Potentials (ERPs) are derived from continuous EEG recordings in experimental conditions were the EEG recording is time-locked to stimulus

presentations. The averaging of many similar stimulus trials (30+) generates an ERP waveform. The presentation of experimental stimuli and the recording of brain activity are performed in parallel. With millisecond accuracy ERPs can be used to examine the on-line processes that separate stimulus processing from a behavioural response. In this way, the processes involved in the initial perceptual analysis, actualisation, response computation and response production for a task can be separated out.

## 3.1.2 Signal Acquisition

EEG recordings are taken from cutaneous electrodes positioned on the scalp in specific locations. Conventional notation makes the electrode positions identifiable across participants (10-20 system and extended 10-20 system; (American, 1994; Jasper, 1958). The location of each of the electrodes is determined by a series of letters and numbers. The letters index the underlying cortical region: 'AF' (anterior frontal), 'FP' (frontal polar), 'F' (frontal), 'C' (central), 'T' (temporal), 'P' (parietal) or 'O' (occipital). The electrodes over the left hemisphere are labeled with consecutive odd numbers extending laterally from the midline, whereas even numbers identify electrodes over the right hemi-scalp. The midline electrodes are tagged with a subscript z instead of a number (see Figure 3.1). Electrodes can be individually positioned on the scalp and fixed in place with an adhesive (e.g. collodion), connected together by small flexible wires in a net (e.g. geodesic sensor nets; (Tucker, 1993) or fixed to a tight fitting cap (e.g. Easy cap, Falk Minow, Germany).

In addition to scalp electrodes, electrodes can be connected above and below (Vertical Electro-oculogram, VEOG) and either side (Horizontal Electro-oculogram, HEOG) of one eye, measuring the electrical potentials produced by eye movements.



Figure 3.1 - Diagram of electrode positions according to the extended 10-20 system for 64 channels (American, 1994).

Electrophysiological recordings require that a stable electro-chemical path be established between the surface of the scalp and the electrodes. This is accomplished with the use of an electrolyte gel. The resistance or impedance of the conducting 'bridge' between the scalp and electrode needs to be minimised. The skin also produces its own potentials that can affect the quality of the recorded brain potentials. Degreasing and abrading the scalp minimises the impedances between the electrodes and the scalp and also prevents the recording of skin potentials (Stern, Ray, & Quigley, 2000).

The voltage variations produced by the brain over the scalp are very small and need to be amplified before they can be recorded. As such, the signal can not travel

very far from the source before being reduced to unrecordable levels and therefore needs to be amplified a short distance from the surface of the scalp.

Raw EEG data contains many environmental artefacts that can include electrical noise (50 Hz in the UK) and movement from the participant. Muscle contractions for example, produce electrical potentials much larger than those created by the brain and therefore must either be removed or corrected before the signal is averaged. If not removed these artifact trials will greatly influence the grand averages calculated for conditions and participants.

# 3.2 Insights from ERP studies of Developmental Dyslexia

Based on the cognitive processes believed to be essential for reading (see Chapters 1 and 2) ERP studies have examined potential visual perceptual, auditory perceptual, language specific and general cognitive deficits in dyslexic children and adults. While behavioural studies are limited to measuring the end product of these different processes (i.e. reaction times), ERP recording enables the temporal dynamics of these processes to be analysed with millisecond resolution.

A range of ERP components have been identified to examine functional impairments at different levels of stimulus processing. Perceptual processing is traditionally measured in paradigms involving inactive tasks that measure ERP responses to passively viewed or heard stimuli (visual and auditory evoked potentials). In contrast, ERP measures of higher cognitive or language specific processes often rely on the active discrimination and identification of target stimuli in an attempt to modulate ERP components indexing stimulus evaluation and working memory.

## **3.2.1 Visual Perceptual Processing**

The traditional visual evoked potential (VEP) response measured to a flashed (transient) checkerboard is composed of a sharp negative peak occurring at around 100 ms after stimulus onset (N100), followed by a broader positive deflection peaking around 200 ms (P200), whereas a diffuse un-patterned or blurred stimulus induces a single positive deflection at 100 ms (P100, Harter & White, 1968, 1970). Sharp checkerboard patterns presented while alternating the checks between black and white (reversal-patterns) elicit the same P100 component, with an additional positive peak at around 200 ms for small check sizes only (P200, White, White, & Hintze, 1983). The amplitudes and latencies of these components are variable across participants, although they are relativity invariant within participants presented with the same stimuli (Spekreijse, van der Twell, & Zuidema, 1973; White & White, 1995).

The visual N100 is thought to reflect stimulus discrimination processing and the initial orienting of spatial attention (Hillyard, Mangun, Woldorff, & Luck, 1995; Vogel & Luck, 2000). N100 amplitude and latency is predominantly modulated by changes in spatial stimulus properties (e.g. spatial frequency) as well as the eccentricity of stimulus presentation (Ermolaev & Kleinman, 1984). In contrast the P100 seems to be modulated by distinct attentional processes (Coull, 1998; Luck, Heinze, Mangun, & Hillyard, 1990; Luck & Hillyard, 1995) being more affected by both spatial and non-spatial stimulus properties (e.g. spatial frequency and contrast) than the N100 (Kurita-Tashima, Tobimatsu, Nakayama-Hiromatsu, & Kato, 1992). Consistent with the functional properties of these components, source analysis and fMRI measures show both the visual N100 and P100 components are mediated by activity from the primary (V1) and peristriate visual cortices (Bonmassar et al., 2001; Maier, Dagnelie, Spekreijse, & van Dijk, 1987).

Differences in the amplitude and latency of the N100 component have been independently observed in dyslexic children and adults in both passive and active visual processing tasks. Using a passive reversal paradigm Hennighausen, Remschmidt and Warnke (1994) recorded VEP responses in dyslexic children to a slowly reversing (1 reversal every 3 seconds) low spatial frequency concentric rectangle pattern (.22 x .25 cycles per degree of visual angle). Hennighausen *et al.* (1994) observed a substantial N100 component in 80 percent of the control participants, but only 44 percent of the dyslexic participants presented with a similar deflection. Overall the N100 was reduced in the dyslexic children as compared with the controls, with a greater reduction identified in those dyslexic children with spelling scores 1.5 standard deviations below their full-scale IQ score (often referred to as discrepancy defined dyslexics).

Presenting a transient checkerboard of varying check sizes from 3.75 to 90 min of visual angle, Meccacci, Sechi and Levi (1983) showed a reduction in peak-topeak amplitudes of the N1-P2 complex in dyslexic participants across all check sizes in both hemispheres. This effect was compounded by differences in hemispheric dominance. Correlations present between the N1-P2 responses recorded over each hemisphere in control participants were absent in dyslexic participants. However, the direction of this effect was not consistent with 25% of the dyslexic participants showing symmetrical but reduced VEPs, 31% showing left hemisphere dominance and 44% right hemisphere dominance. In a later study examining intrasensory integration of binocular visual information in dyslexic children, Solan and colleagues (1990) showed an overall reduction in the P100 to binocular and monocular presentations in dyslexic children over controls. Interestingly, the same dyslexic

children also showed an increased binocular advantage in P100 amplitude that was not present for the controls.

Studies focusing on differences in visual word processing have also shown delays in the N100 for non-linguistic 'control' stimuli as well as word stimuli in dyslexic participants (Breznitz & Meyler, 2003; Breznitz & Misra, 2003; Cohen & Breslin, 1984; Robichon, Besson, & Habib, 2002), although this effect is not always observed (Csepe, Szucs, & Honbolygo, 2003).

Following the proposal of a magnocellular deficit in dyslexia, further studies have examined the VEP response of dyslexic children and adults, this time focusing on those stimulus parameters thought to predominantly be affected by magnocellular function. As non-human studies show magnocells predominately respond to transient, low spatial frequency and low luminance contrast stimuli, these parameters have been varied systematically in VEP studies examining dyslexia. In one such study, Livingstone, Rosen, Drislane and Galaburda (1991) report a delayed P100 in dyslexic adults for rapid contrast reversal patterns (1 reversal per second) for low but not high contrast stimuli with the same spatial frequency. Whereas examining changes in spatial frequency Lehmkuhle, Garzia, Turner and Hash (1993) report longer P1 and N1 latencies for dyslexic children in response to low, but not high spatial frequency targets. Brecelj, Strucl and Raic (1996) examined VEP responses to a range of rapid (4 per second) checkerboard reversal patterns with a range of spatial frequencies and luminance contrasts in dyslexic children. They found a significant prolongation of the P100 in the dyslexic children for the highest contrast and lowest spatial frequency stimulus only. The findings of these studies are consistent with a specific magnocellular visual deficit. However, not all studies have found effects for stimuli that should be predominantly processed by the magnocellular system. Brannan, Solan,

Ficarra & Ong (1998) report lower P1 amplitudes to checkerboard reversal patterns across a range of temporal frequencies (1, 4, 8Hz) and in high and low luminance contrasts, as well as to a 8Hz flicker fusion stimulus. Furthermore, some studies have failed to find any differences in VEP amplitudes between control and dyslexic participants: Using similar luminance and contrast changes to Livingstone *et al.* (1991), Victor, Conte, Burton and Nass (1993) found no VEP differences in dyslexic participants for steady-state or transient contrast-reversal patterns. Similarly, Schulte-Koerne, Bartling, Deimel and Remschmidt (1999) found no group differences between dyslexic and control adults in N1 or P1 amplitudes over a range of spatial frequencies and contrast levels.

Unfortunately little is known about the relative contributions of the magnocellular and parvocellular systems to the VEP response. Recent research by Ellemberg, Hammarrenger, Lepore, Roy and Guillemot (2001) suggests that contributions of the magnocellular and parvocellular systems to VEPs are present over a wide range of spatial frequencies (although not necessarily in equal proportions). Ellemberg *et al.* found that the VEP response to different contrast levels is only consistent with that expected of the magnocellular system at very low spatial frequencies (0.8 c deg<sup>-1</sup>). Furthermore, little is known about the adaptation dynamics of VEPs. This is especially important when considering that different spatial frequencies may result in different levels of VEP habituation (Heinrich & Bach, 2001).

In normal adults VEP amplitudes have been shown to vary naturally with spatial frequency, maximal amplitudes being achieved for check sizes of approximately 15 min of visual angle with greater and smaller check sizes resulting in smaller VEP component amplitudes. Arguably, the noise associated with

heterogeneous clinical populations such as dyslexic adults would allow predicting differences in extreme check sizes where the VEP amplitudes are small, irrespective of predominate magnocellular or parvocellular function.

Comparatively smaller N1 components in dyslexic participants have been consistently interpreted as representative of sensory deficiencies, with little regard for the task being performed. Importantly, the larger N1 and P1 amplitudes observed in control participants for active (attention requiring) tasks could equally be the result of a lack of attentional enhancement in the dyslexic participants rather than a reduction in sensory discrimination abilities. This may account for the variability in N1 and P1 differences observed in dyslexic and control participants in passive tasks, where spontaneous shifts of attention are uncontrolled.

In sum, VEP differences have been reported for various visual stimuli in dyslexic participants which support the presence of a perceptual or possibly attentional visual processing deficit in dyslexic individuals. However these deficits are not limited to stimuli that should predominately activate the magnocellular system. Furthermore, there is little evidence to suggest that these differences in visual processing relate to the reading or spelling difficulties experienced by dyslexic individuals.

## 3.2.2 Auditory Perceptual Processing

ERP measures of potential perceptual deficits in developmental dyslexia have not been limited to the visual modality. Sensory components elicited by simple auditory stimuli (auditory evoked potentials, AEPs) consist of an earlier and greatly reduced P1 than observed in VEPs (peaking at approximately 50 ms after stimulus onset) followed by a sharp N1 peaking at around 100 ms. Similar to the N1 elicited by

visual stimuli, the auditory N1 is thought to reflect initial perceptual processing and unconscious focusing of attention (Davis & Zerlin, 1966; Hillyard, Hink, Schwent, & Picton, 1973). However, the auditory N1 is composed of signals from multiple generators, some of which are more greatly modulated by discriminative stimulus changes than the habituation of sensory processes (Näätänen & Picton, 1987). Following the N1, simple auditory stimuli also elicit a P2-N2 complex. The P2 peaks at around 200 ms and is thought to index the building/scanning of transient working memory representations (e.g., Conley, Michalewski, & Starr, 1999; Gevins et al., 1996; Smith, 1993). Both the N100 and N200 are modulated by discriminable changes in auditory stimuli. This modulation, termed the mismatch negativity (MMN), provides an index of automatic change detection in the context of attended or passive auditory oddball paradigms (series of identical stimuli or 'standards' interrupted by low probability stimuli 'deviants', Näätänen, 1995). The MMN is measured as the difference in amplitude between AEPs elicited by frequent (standard) stimuli and oddball (deviant) stimuli. It has been reported for changes in pitch, duration and volume (Näätänen, 1992). Furthermore, the MMN indexes behavioural discrimination performance and varies with the discriminability of a stimulus, being largest for most discriminable stimuli (Amenedo & Escera, 2000; Tiitinen, May, Reinikainen, & Näätänen, 1994).

Early studies of simple auditory processing in dyslexic children have focused on passive listening tasks that elicited clear AEPs. Pinkerton, Watson and McClelland (1989) examined the AEPs of 'poor readers' while they passively listened to a series of 2000 Hz pure tones presented at a rate of 2 per second. In their study, 'Poor readers' not diagnosed as dyslexic showed a reduced P1 and N1 to tones. In addition, the amplitude of the N1 correlated with participants' performance on a battery of

cognitive assessment measures including spelling, reading, comprehension and performance IQ. Pinkerton *et al.* (1989) interpreted the attenuated P1 as reflecting a deficit in auditory processing and the concurrent reduction of the N1 as a disruption in the focusing of attention. However, in a passive task where participants are not required to focus attention, any changes in attentional focus are likely to result from top-down irrelevant processes which are likely to vary greatly across individuals. In another passive AEP study, using clear diagnostic criteria in the selection of dyslexic participants Yingling, Galin, Fein, Peltzman and Davenport (1986) reported no difference in the AEPs recorded to a series of slowly presented auditory 'clicks'(1 per second). If deficits in the focusing of attention underlie the poor reading performance of dyslexic participants, similar performance would be expected in both the Pinkerton *et al.* and Yingling *et al.* studies. However, this does not discount the possibility of a deficit in the shifting of attention which may show as a reduction in the N100 limited to the faster stimulus presented used in the study by Pinkerton et al. (1989).

Examining early auditory evoked responses to complex acoustic stimuli McAnally and Stein (1996) found reduced AEPs in reponse to phase-locked spectral changes (frequency discriminations) in dyslexic participants. In a subsequent study McAnally and Stein (1997) also recorded auditory evoked potentials to amplitude modulated tones which they found to be significantly reduced in dyslexic participants, while auditory brain stem responses to a sequence of clicks was similar in all participants. These findings are indicative of a temporal processing deficit in dyslexic participants for rapid spectral changes.

Some studies report similar asymmetries and topographic differences in the AEPs of dyslexic children and adults as reported for VEPs. Using a dichotic listening task Brunswick and Rippon (1994) report similar N100 amplitudes over both

hemispheres for dyslexic children, while controls showed greater amplitudes lateralized over the left temporal region in response to spoken syllables. Despite this neurophysiological difference, dyslexic participants' had similar behavioural performance to that of controls. Brunswick and Rippon (1994) suggest that this disparity between behavioural performance and AEPs indicates a perceptual deficit that influences mechanisms involved later in the reading process. Other studies have found this attenuated activity over the left scalp for a limited subgroup of dyslexic participants with relatively unimpaired phonological spelling skills to linguistic and non-linguistic auditory stimuli (Fried, Tanguay, Boder, Doubleday, & Greensite, 1981; Rosenthal, Boder, & Callaway, 1982).

Passive tasks leave attentional effects which may influence the perception of otherwise discriminable stimulus changes uncontrolled. Therefore active tasks have also been implemented to examine perceptual influences on early auditory components.

In an auditory oddball detection task, Neville, Coffey, Holcomb and Tallal (1993) reported a reduction in the N1 in language impaired children with associated literacy difficulties. In addition, the N1 peaking at around 140 ms in the control children was delayed in the language impaired children. Implementing a similar pure tone oddball paradigm, Bernal, Harmony, Rodriguez, Reyes *et al.* (2000) found no differences in the N100 amplitude or latency in dyslexic children as compared with matched controls. However, Bernal *et al.* (2000) did find differences in the amplitudes of P200 and N200 components in the same dyslexic children. The P200 was enlarged in the dyslexic children in response to both standard and deviant stimuli which were counterbalanced across 1000 Hz and 3000 Hz tones. In contrast, the N200 to deviants was reduced in the dyslexic children. Since all participants received both tones as the

standard and the deviant, this difference in unlikely to be the result of the specific stimulus discrimination. Since the P200 has been shown to be influenced by task demands (e.g. Johnson, 1989), Bernal *et al.* (2000) proposed that a limitation in attentional capacity might be the basis for this effect. Furthermore Bernal *et al.* (2000) proposed that the reduced N200 reflects a deficit in auditory perceptual processing that is caused by the earlier misallocation of attention in dyslexic children.

In order to discount the influence of attention and test the psychoacoustic thresholds of dyslexic children and adults other studies have examined the automatic detection of auditory changes as indexed by the MMN. However, despite suggestions that the MMN is attention independent, recent studies show modulations of the MMN in focused attention tasks that are greater than for passive tasks (Oades & Dittmann-Balcar, 1995; Szymanski, Yund, & Woods, 1999).

Presenting a variety of tone frequencies and durations Baldeweg, Richardson, Watkins, Foale and Gruzelier (1999) observed a delay in MMN latencies and a reduction in MMN area in dyslexic adults to tone frequency changes, but not to changes in tone duration. Furthermore, the MMN difference between dyslexic and control adults became larger as the frequency discrimination became smaller, with no MMN response in dyslexic adults for the smallest discrimination of 15 Hz. Baldeweg *et al.* (1999) also observed a correlation between MMN latencies and scores on regular word and non-word reading, but not cases of irregular word reading (where phonological rules do not cue the correct pronunciation of the word). This study suggests the role of a frequency discrimination deficit in the poor phonological decoding skills of dyslexic adults. Like Baldeweg *et al.*, Huttunen, Halonen, Kaartinen and Lyytinen (as cited in Lyytinen et al., 2005) also failed to find differences in MMN amplitude or latency in dyslexic children for discriminable

changes in tone duration. However they did observe differences in the laterality of the MMN response for tone duration that varied between the groups.

In a series of independent studies Schulte-Körne, Deimel, Bartling and Remschmidt (1998; 1999; 2001) reported a reduction in MMN amplitudes for rapid tonal patterns but not slowly presented pure tones in dyslexic children and adults. Using a passive oddball paradigm Schulte-Körne et al. (1998) failed to find any reduction in the MMN elicited by short (90 ms) 1050 Hz deviant pure tones amongst 1000 Hz standards in dyslexic children compared with controls. However, a reduced MMN was observed in the same dyslexic children in response to oddball CV syllables (/ba/ deviants and /da/ standards) compared with controls. Importantly, when the same long inter-stimulus interval (590 ms) and stimulus duration (90 ms) was used with higher frequency pure tone deviants (2640 Hz) and standards (2200Hz) no significant differences were observed in the MMN amplitudes between dyslexic adults and controls (Schulte-Korne, Deimel, Bartling, & Remschmidt, 2001). However, a significantly reduced MMN was observed in dyslexic adults compared with controls in response to oddball synthetic CV syllables (/ga/ deviants and /da/ standards) which were longer than the previously used tones (110 ms). Arguably, the results of these studies support a speech specific perception deficit that may be the result of impaired processing of rapid spectral changes required for the discrimination of phonemes but not pure tones. Finally, Schulte-Körne, Deimel, Bartling and Remschmidt (1999) presented dyslexic adults with discriminable tonal patterns created from a sequence of 4 tones of different durations. Deviant tonal patterns were composed of the same 4 frequency tone sequence as the standards, but with the duration of the second and fourth tones permutated. Schulte-Körne et al. (1999) propose that the reduced MMN in dyslexic participants is indicative of a temporal processing deficiency for patterned

auditory stimuli such as phoneme sequences in words. However, perceptual discrimination of these tonal patterns indexed by the MMN requires the segmentation or disambiguation of the individual tones as well as the perception of changes in duration, for which dyslexic adults seem unimpaired (Baldeweg, Richardson, Watkins, Foale, & Gruzelier, 1999). Following this Kujala, Myllyviita, Tervaniemi, Alho, Kallio and Näätänen (2000) examined the MMN responses of dyslexic adults to the detection of deviant tone-pair and 4-tone-pattern stimuli. Deviant stimuli differed from the standards based on the duration of silence between tones. Consistent with the proposal of a deficit in the discrimination of temporal changes in multi-item auditory stimuli like words (Schulte-Korne, Deimel, Bartling, & Remschmidt, 1999), Kujala et al. (2000) observed a reduction of the MMN in dyslexic adults to the 4-tone-pattern stimuli, but not the tone-pair stimuli. In a further investigation Kujala, Belitz, Tervaniemi and Näätänen (2003) examined the MMN response in dyslexic adults to single tones, tone-pairs and tone-pairs with an additional forward or backward masking tone of same duration but different frequency. Kujala et al. (2003) observed a reduction in the MMN response of dyslexic participants restricted to left lateralized electrode sites for single tone deviants. However, they failed to find any reduction in the MMN for deviant reversals of tone-pairs or forward masked tone-pairs, but did observe a reduced MMN in the dyslexic adults in response to backward masked tonepairs. These backward masking effects are possibly the result of an increased window of auditory integration in dyslexic individuals (i.e. the perception of one tone is more effected by the presentation of successive tones in dyslexic participants than controls, Hari & Renvall, 2001).

In addition to the assessment of perceptual auditory processing in dyslexic children and adults several studies have attempted to examine for ERP markers of

dyslexia in infancy, before formal diagnosis using a battery of psychometric tests is possible. To do this authors have examined the auditory processing abilities of infants with familial risk of dyslexia, i.e., infants whose parents or siblings have been formally diagnosed with dyslexia (e.g. Leppanen, Pihko, Eklund, & Lyytinen, 1999; Leppanen et al., 2002). In one such recent example, Maurer, Bucher, Brem and Brandeis (2003) report a reduced MMN to changes in tone frequency and spoken syllables in 'at risk' children. Interestingly this reduction was greater for tone frequency changes than syllable changes, despite both being presented at the same rate and for the duration. Unfortunately, very little can be inferred from differences in 'at risk' infants. Without knowledge of the subsequent reading performance of these infants, differences in MMN responses may be subtle indicators of risk that only rarely lead to dyslexic difficulties. There is however, some evidence to suggest a causal relationship between an auditory perceptual deficit as indexed by a reduced MMN in dyslexic participants as compared with controls, and poor reading performance. Implementing an audio-visual training program with a relatively large group of dyslexic children, Kujala, Karma, Ceponiene, Belitz, Turkkila, Tervaniemi and Näätänen (2001) reported enhanced MMN amplitudes in dyslexic children that accompanied improvements in reading.

In summary, there is strong evidence in support of the presence of an auditory perceptual deficit in dyslexic children and adults. However, the specific nature of this deficit is unclear, since discriminations based on both spectral and temporal stimulus properties have given rise to reduced MMN amplitudes in dyslexic participants as compared with controls. Predominately, MMN differences in auditory discrimination between dyslexic and control participants have been found for rapidly presented stimuli with short durations, and it is MMN amplitudes recorded to these

discriminations which have been shown to correlate with measures of phonological skill (e.g. non-word reading). However, similar reduced MMN amplitudes found for dyslexic participants have also been observed for participants with other developmental disorders (e.g. ADHD, Kemner et al., 1996; Kilpelainen, Partanen, & Karhu, 1999; Winsberg, Javitt, Silipo, & Doneshka, 1993). Therefore, tone discrimination difficulties indexed by the MMN may be the result of a deficit in attention in dyslexic participants which is important for reading performance (Kilpelainen, Partanen, & Karhu, 1999).

#### 3.2.3 Language Specific Processing

The investigation of language specific deficits has examined both auditory (phonological) and visual (orthographic) form processing as well conceptual (semantic) processing. Several *ad hoc* ERP components sensitive to language have been identified, but these components are by no means specific to linguistic stimuli. The N400 for instance, which was initially thought to reflect semantic processing, has been identified in tasks measuring non-verbal conceptual processing (West & Holcomb, 2002). ERP studies examining language processing in dyslexia have focused on the modulation of components sensitive to changes in discrimination, working memory and expectancy such as the N200, N400, P300 and P600 elicited by linguistic stimuli in various cognitive contexts.

The N400 component has been reported in many ERP studies of language and is thought to index a process of semantic or conceptual integration (Friederici, 1997; Kutas & Hillyard, 1980), although some debate exists as to whether it is the result of a pre-lexical or post-lexical integration process (see for example Deacon, Hewitt, Yang, & Nagata, 2000). An enhanced N400 component was originally reported for

semantically incongruent sentence endings as compared to semantically congruent ones (Kutas & Hillyard, 1980) and has since been shown to be modulated by both semantic and phonological priming within pairs of items (Holcomb & Neville, 1990; Rugg, 1984a, 1984b; Silva-Pereyra et al., 1999). The N400 modulation is typically regarded as an index of the semantic expectancy of a stimulus in the context in which it is presented (Kutas & Hillyard, 1984; Van Petten, Coulson, Rubin, Plante, & Parks, 1999). Anomalous sentence endings and unprimed stimulus words in a semantic judgment task elicit a greater N400 than highly expected and primed stimulus words. The N400 observed for incompatible pairs of auditory or visually presented words is typically distributed over fronto-central or centro-parietal regions, respectively. In addition, the N400 onsets earlier and has a longer duration in response to auditory than visually presented words (Holcomb & Neville, 1990). Consequently it has proved difficult to discern separate N200 and N400 peaks in response to auditory words. However, several studies have attempted to discriminate two deflections within the N400 time window representative of a fronto-centrally distributed N200 and centrally (or centro-parietally) distributed N400 (Connolly, Phillips, Stewart, & Brake, 1992; Connolly, Stewart, & Phillips, 1990). Using auditory presented sentences Connolly and Phillips (1994) were able to functionally separate the N200 and N400 components by parametrically manipulating the semantic and phonological expectancy (first phoneme) of the last word in sentences. The N200 peaked between 270 and 300 ms after stimulus onset and was selectively modulated by phonological expectancy, whereas the N400 peaking around 400 ms was modulated by semantic expectancy.

The N400 can also be observed for passively viewed or heard semantic and phonological violations. Phonological priming in response to non-phonological tasks

(e.g. lexical decision) for auditory and visually presented words suggests that the N400 modulation occurs automatically (in the absence of conscious attention) in the process of word recognition (Praamstra & Stegeman, 1993; Rugg, 1984a, 1984b).

In order to examine lexical/ semantic integration in dyslexic children a number of authors have used tasks requiring the identification or discrimination of written letters or words. In one such study, Ackerman, Dykman and Oglesby (1994) presented a visual rhyme judgment task containing words and pseudo-words to three distinct groups of children. Age and IQ discrepant dyslexic children were compared with a group of non-discrepant poor readers and a group of attention deficit disorder (ADD) children without any reading difficulties. Consistent with a deficit in phonological processing Ackerman *et al.* (1994) showed a reduction in the N450 (N400) for word and pseudo-word rhymes in dyslexic children only. However, further analysis revealed that dyslexic participants showed a typical N400 enhancement to non-rhyming pseudo-word pairs but not to real word pairs. Although still indicative of a phonological impairment in the dyslexic participants, the absence of an N400 effect to real-word pairs implies a deficit in lexical rather than sub-lexical phonological processes required for reading pseudo-words.

In order to examine the relative influences of phonological and orthographic processing deficits in dyslexic children McPherson, Ackerman, Holcomb and Dykman (1998) compared both visual and auditory word rhyming tasks, while orthogonally manipulating orthographic priming. In addition, McPherson *et al.* (1998) categorised their dyslexic participants into subtypes based on their non-word reading skills; phonetics (good decoding skills) and dysphonetics (poor decoding skills). In the visual task controls showed both a left-ward contingent negative variation (CNV) indexing response preparation prior to target presentation and the classical N400

enhancement to both orthographic and phonological foils. Consistent with their poorer phonological skills in non-word reading the dysphonetic children showed a similar CNV and N400 enhancement to orthographic foils, but had a significantly reduced N400 for phonological unprimed (non-rhyming) targets. In contrast the phonetics showed normal N400 enhancement for both orthographic and phonological foils, but displayed a reduced CNV. In the auditory task controls and dysphonetics displayed a similar N400 priming effect which was significantly delayed in the phonetics. McPherson et al. (1998) argue that the delayed N400 and longer RTs in the phonetic children suggest a deficit relating to speed of processing or inadequate response preparation, whereas dysphonetics seem to have difficulty translating orthography into phonology and not pure phonological processing (auditory task). In another sample of similarly categorized dyslexic participants (poor versus good phonological decoders) McPherson and Ackerman (1996) also failed to find a N400 priming effect for pictures whose names rhymed in dyslexic participants with poor phonological skills. In addition to the findings of McPherson et al. (1998) the absence of an N400 priming effect for pictures suggests a phonological deficit relating to the initiation of phonological units during lexical access, rather than a deficit in the processing of heard words.

Following the delayed N400 observed in dyslexic children with good nonword reading performance (McPherson, Ackerman, Holcomb, & Dykman, 1998), Breznitz and Misra (2003) found delays in the P200 and P300 for dyslexic children who performed poorly on tests of decoding (including timed non-word reading). Substantial latency differences in ERP components and subsequent behavioural performance suggest that impairments in phonological and orthographic processing may not be limited to deficits in processing capacity (Breznitz & Misra, 2003).

Instead, the smooth interaction between phonology and orthography may be impeded by differences in the temporal relationship between these two processes. Presenting dyslexic children with a series of visual and auditory detection tasks, Breznitz and Misra (2003) observed delays in the P300 to both auditory pure tone and phoneme detection tasks and delays in the P200 to lexical decision tasks.

In addition to phonological and orthographic processing, semantic access is central to the comprehension of written words. Furthermore, semantic processing influences the decoding of written words through top-down mechanisms. This is especially true for irregular words, where the sentence semantic context rather than phonological conversion rules are required to access the correct pronunciation of words.

To evaluate semantic processing in dyslexic participants Stelmack and Miles (1990) presented dyslexic and control participants with line-drawings of objects that either did or did not associatively prime a subsequently presented written word. They observed a classical N400 enhancement to unprimed words in control participants which was reduced in dyslexic participants, although primed words resulted in similar N400 reductions in dyslexic and control participants. In a further study Miles and Stelmack (1994) using the same visual semantic priming task and an additional spoken word semantic priming task failed to observe an N400 priming effect to visual or spoken word primes in dyslexic participants. Furthermore, a subgroup of participants identified with arithmetical difficulties but normal reading and spelling skills showed a N400 priming effect for the spoken word primes only. These results cast doubt on the presence of a semantic processing deficit specific to dyslexic individuals.

Lovrich and Cheng (1997) compared the performance of dyslexic adults and controls on serially presented spoken rhyme judgement and semantic judgement tasks. The N400 amplitude was larger in dyslexic participants compared with controls in the rhyme judgement task. However, no N400 differences were found between dyslexic and control participants in the semantic judgement task. These results support the presence of a deficit in phonological processing, but not semantic processing. Therefore, differences in N400 amplitudes between dyslexic and control participants may be representative of the differences in the underlying phonological processes used to access semantics and not semantic processing *perse*.

Access to the stored lexical representations of words is a relatively automatic process in the skilled reader. Therefore investigation of lexical access, lexical selection and the transition to semantic access are highly relevant to the understanding of dyslexia. Lexical effects have been shown to induce ERP modulations as early as 150 ms after the presentation of a visual word, but are also found much later in the N400 range (Proverbio, Vecchi, & Zani, 2004; Rugg, 1990). The experience of a word may also have an effect on how easily its lexical representation is accessed. Therefore, high frequency words result in decreased N400 amplitudes as compared with low frequency words, although this effect is almost completely abolished when words are repeated (Rugg, 1990; Rugg & Doyle, 1992).

Examining the word frequency effect in dyslexic adults Johannes, Mangun, Kussmaul and Münte (1995) observed a greater reduction in the N400 to high frequency words in dyslexic adults as compared with controls. Furthermore, this effect was undisrupted for repetitions of the words in the dyslexic participants. Since the efficiency of lexical retrieval is thought to be influenced by word frequency, Johannes *et al.* (1995) speculated that dyslexic adults use frequency information for

the integration of sentence context much more than control participants, possibly in compensation of impaired phonological processes for word recognition. Other studies have also observed ERP differences likely to relate to lexical access and selection. Csepe, Szucs and Honbolygo (2003) examined ERP responses in dyslexic adults performing a lexical decision task on words, number-words and pseudo-words. Consistent with the findings of Johannes *et al.* (1995), Csepe *et al.* (2003) observed the largest ERP differences between dyslexic and control adults for high frequency (number) words, although these differences were observed prior to the classical N400 time window.

Based on the hypothesis that semantic integration processes influence reading performance and fluency, Chayo-Dichy, Ostrosky-Solis, Meneses, Harmony and Miguel (1991) examined differences in the ERPs of dyslexic children reading three word sentences in which final word expectancy was high and single word reading (where words could not be anticipated from a semantic context). They found ERP component reductions over the left occipital region (O1) for sentence reading across all three words, but not for single word reading. This suggests that dyslexic participants may not use sentence-level semantic cues in the same way as control children.

Further studies of lexical expectancy have focused on sentence reading where sentences are presented visually one word at a time, often with semantically congruent or incongruent terminal words. In one such study, Robichon and Besson (2002) observed an increased N400 in dyslexic adults compared with controls at slow (but not fast) presentation rates that was independent of semantic congruency. Robichon and Besson (2002) proposed that this was evidence of impaired contextual integration in the dyslexic participants. However, an N400 enhancement limited to

slowly presented words and present for both congruent and congruent sentence endings is also consistent with greater semantic search in the dyslexic children than the controls. In contrast, other authors have shown delays in the N400 in response to anomalous sentence endings only, which could be the result of an impairment in contextual semantic integration processes in dyslexic children (Brandeis, Vitacco, & Steinhausen, 1994).

Further studies have also observed reductions in ERP amplitudes in tasks involving lexical (Barnea, Lamm, Epstein, & Pratt, 1994) and semantic (Stelmack, Saxe, Noldy-Cullum, Campbell, & Armitage, 1988) recognition memory. Barnea *et al.* (1994) observed a reduced P300 in dyslexic children as compared to controls in the recognition of digits from a probe stimulus set, but not novel characters. Stelmack, Saxe, Noldy-Cullum, Campbell and Armitage (1988) on the other hand observed a reduction in the N400 in dyslexic participants for probe words and word recognition trials in the absence of any P300 differences between the groups. These results suggest dyslexic individuals have deficient lexical representations which manifest impairments in semantic and lexical judgments.

Some ERP studies have examined hypothetical syntactic or morphological processing deficits in developmental dyslexia (see Breznitz & Leikin, 2000). However, it is difficult to explain how such deficits may be linked to reading and spelling deficits observed in dyslexia, particularly at the single word level. Breznitz and Leikin (2000) presented Hebrew-speaking dyslexic adults with sentences of a limited syntactic order (subject-verb-object) and observed increased N100 and P300 amplitudes and latencies in dyslexic adults to the subject word as compared to the verb or object words. Breznitz and Leiken (2000) interpret these results are consistent with the presence of a syntactic processing deficit in dyslexia. However, the delays in

N100 and P300 they observed in dyslexic participants as compared to controls may reflect differences in stimulus evaluation and working memory updating processes independent of syntactic or morphological processing deficits. Consistent with the later interpretation, Breznitz and Leikin (2000) in a subsequent experiment observed contrastingly shorter latencies of the P300 in dyslexic adults as compared with matched controls to similar but more rapidly presented subject-verb-object sentences.

In sum, despite prominent deficits in reading and spelling the specificity of dyslexia as an impairment in the processing of linguistic stimuli has not been established. Therefore some studies have attempted to compare linguistic and complex non-linguistic tasks, to test the specificity of the deficits in dyslexia to language.

Comparing form (letter shape identification) and phonological (letter rhyme identification) tasks, Lovrich, Cheng and Velting (2003) were surprised to observe a reduced N200 and N400 in dyslexic participants for both the form and phonological tasks. Reduced component amplitudes for a simple visual discrimination task suggest a non-specific visual processing deficit in dyslexic children. However, differences in reaction times between dyslexic and control participants were only observed for the phonological task.

In contrast, Rüsseler, Probst, Johannes and Münte (2003) observed reductions in the N400 for recognition memory of high and low frequency words in dyslexic participants compared to controls. Whereas in a separate study no differences between dyslexic and control participants were found for the recall of complex non-linguistic visual stimuli (e.g. Faces, Rüsseler, Johannes, & Münte, 2003). However, these tasks were performed on separate dyslexic populations and were not matched for task complexity or the type of discrimination processes and memory demands involved.

Importantly, face recognition has been hypothesized to recruit different memory processes from word retrieval (for a review see Rapcsak, 2003). Using a more controlled comparison, Greenham, Stelmack, van der Vlugt (2003) observed a reduced N450 in dyslexic children naming visually presented words and semantically associated picture-word displays, but not individually presented pictures, compared with control participants. This suggests that dyslexic children are impaired for the processing of specific lexical stimuli and not more general cognitive processes. However, Taylor and Keenan (1990) report a delayed N200 and P300 for dyslexic children compared with controls in non-verbal (symbol) and language (letter) categorization tasks.

In summary, many studies have examined for the presence of lexical impairments in dyslexic children and adults. Differences in the N400/ N450 in dyslexic children compared to controls support the presence of a lexical-semantic deficit in dyslexic individuals. However, this deficit may be the result of poor reading skill and phonological processing rather than the cause. Where studies have focused on phonological and orthographic processing, strong differences between dyslexic and control participants have been readily observed. Furthermore, when compared with complex non-linguistic tasks these deficits are generally found to be restricted to language stimuli, although not always.

# 3.3.4 General Cognitive Processing

In addition to language specific changes in ERP components, ERP modulations reflecting the general cognitive processes subserving the reading system have also been investigated. Due to their global impact on the cognitive system, attention and memory resources have an effect on both the fluency and accuracy of

language processing. The complex orchestration of multiple cognitive subsystems in reading means that it is particularly susceptible to impairment from general cognitive deficits.

Attentional processes are dependent on task demands and modulated by stimulus perception, especially in stimulus discrimination tasks. Studies addressing the issue of attentional differences between dyslexic children, control children and adults have examined higher-order stimulus discrimination processes as indexed by the P300 for example, and lower-level sensory ERP components (e.g. N100 and P200) differences between active demanding tasks and passive tasks. In one such study, Harter, Diering and Wood (1988) studied visual selective attention in dyslexic children by examining differences in ERPs elicited by passive observation and active colour detection or letter identification for black and white letters and non-letters. Harter *et al.* (1988) found reduced differences between passive observation and active task performance at around 200 ms (P200) and 500 ms for dyslexic participants compared with controls. Harter *et al.* (1988) suggest that these differences are indicative of a general selective attention deficit in dyslexic children. However, measures of attention using the subtraction of passive tasks (where attention is uncontrolled) from active ones can inaccurately report the effect of attention.

A majority of studies assessing the attentional resources of dyslexic children and adults have examined ERP responses to the classical oddball task. The presentation of an infrequent and discriminable stimulus change in an otherwise consistent stimulus stream gives rise to a component peaking between 300 and 700 ms on average and distributed over centro-parietal regions (P300 or P3b), dependent on the ease of discrimination, task complexity and modality of presentation (Kok, 2001). In contrast, task irrelevant 'novel' stimulus changes presented in a series of
standard stimuli elicit a component peaking between 300 and 400 ms on average and distributed over fronto-central regions (novelty P3 or P3a, Squires, Squires, & Hillyard, 1975).

Lovrich and Stamm (1983) examined auditory selective and sustained attention to brief tones (40 ms) in dyslexic and control children. Sustained attention was measured behavioural by the detection of higher pitch oddballs (1500 Hz standards and 1560 Hz target deviants), whereas ERP and behavioural measures of selective attention were examined in the context of a dichotic listening task. In the dichotic listening task participants responded to the detection of oddball targets in one ear only, while ignoring oddball targets of a different pitch presented in the other ear. Slower reaction times in the sustained attention task discriminated dyslexic and control participants, however no reaction time differences were found between dyslexic and control participants in the selective attention task. A P3 modulation observed in response to infrequent tones presented in the attended ear was reduced in dyslexic participants compared with controls. An N400 modulation was also observed for the attended compared with the unattended condition, however this response was similar for dyslexic and control participants. Mazzotta and Gallai (1992) found a reduced and delayed P300 in dyslexic children compared with controls for the detection of pure tone oddballs, whereas in a similar oddball task, Bernal, Harmony, Rodriguez et al. (Bernal et al., 2000) failed to show any differences in the P3 amplitude between dyslexic children and controls.

Presenting a 3-stimulus oddball task (80 % standard, 10 % target tones and 10 % novel task irrelevant sounds) Rüsseler, Kowalczuk, Johannes *et al.* (2002) found enhanced P3a amplitudes in dyslexic participants compared with controls to novel stimuli. However, they failed to find any differences between dyslexic and control

participants in P3b amplitudes to target pitch oddballs. Furthermore, passive listening to the same oddball series failed to elicit P3a differences between dyslexic and control participants. Russeler *et al.* (2002) argue that increased distractibility in the dyslexic participants to the novel tones is the most likely explanation of their results.

Unfortunately, many of these studies have failed to control for the presence of co-morbid disorders that may affect general attention processing independent of reading difficulties (e.g. ADHD). In an auditory and visual oddball paradigm Duncan, Rumsey, Wilkniss *et al.* (1994) examined the performance of dyslexic and control adults assessed on measures of ADHD symptoms as well as reading and spelling. In addition, response demands for the visual and auditory oddball task were varied to assess the effects of task difficulty. Participants were either not required to make a response, respond only to the oddballs, or make one response for the oddballs and another for the standards. The P300 was reduced in dyslexic participants compared with controls in the visual task, an effect that increased with greater task difficulty. However, further analysis revealed that only those participants scoring high for ADHD symptoms showed a P300 amplitude significantly smaller than controls. Duncan *et al.* (1994) found no P3 amplitude differences between dyslexic and control participants in response to auditory oddballs.

In contrast to the findings of Duncan *et al.* (1994), Holcomb, Ackerman and Dykman (Holcomb, Ackerman, & Dykman, 1986) found a reduced P3b to pure tone oddballs across three clinical groups (dyslexic, attention disorder without hyperactivity and attention disorder with hyperactivity) compared with controls.

Overall, deficits in attention as indexed by differences in P3a and P3b amplitudes between dyslexic and control participants are inconclusive. Differences in

stimuli, task design and participant selection in these experiments make it difficult to draw any firm conclusions.

### 3.3 Summary of Causal Theories and ERP Insights

Several different cognitive systems and their associated neural substrates have been implicated as the cause of developmental dyslexia. Importantly, these major theories are not mutually exclusive and explain deficits in reading and spelling at multiple levels of explanation (behavioural, cognitive and neural, see Figure 3.2 and U. Frith, 1997, 1999).





The magnocellular theory asserts a neurophysiological basis for temporal processing deficits proposed by the temporal processing theory. However, evidence against the magnocellular theory is not necessarily evidence against the temporal processing theory, which is not confined by the specificity of magnocellular responses to low contrast and low spatial frequency stimuli. Overall there is strong evidence for visual impairments in at least a proportion of dyslexic adults and children; however these deficits are not limited to rapid or low luminance stimuli that predominately activate the MC system. There is some evidence to support the presence of an auditory temporal processing deficit in dyslexic children and adults. However, after controlling for the presence of co-morbid attention and spoken language deficits the majority of these deficits are restricted to speech stimuli.

General attention deficits may relate more directly to impaired reading fluency in dyslexic children and adults, since increases in attention span and working memory accompany faster reading speeds (Breznitz, 1988; Breznitz & Share, 1992). Similarly, while deficits in automaticity could clearly explain fluency impairments in dyslexia, it is difficult to see how they can completely explain deficits in accurate decoding (i.e. non-word reading, which one assumes is not an well practiced skill for anyone). However, the process of sublexical retrieval must to some extent be an automatised during reading development, otherwise the reading of non-words would not come so easy to most people.

Phonological processing deficits are consistently found in a majority of dyslexic participants (Ramus et al., 2003). However, the specificity of this deficit remains unclear. While rapid naming and to some extent speech perception may be seen to rely heavily on whole-word (lexical) phonological processes, performance on non-word reading and phoneme awareness tasks rely more on segmental (sub-lexical) phonological processes (Murphy, Pollatsek, & Well, 1988; for a different view see Peereman, 1991). The wide range of phonological deficits found in developmental dyslexia, particularly for rapid naming and non-word reading suggest impairments in both lexical and sub-lexical processes.

Importantly, dyslexic individuals may be impaired in several independent cognitive processes (e.g. phonological processing and automaticity, Wolf & Bowers, 1999). It follows that deficits in reading fluency and deficits in phonological decoding accuracy may stem from independent impairments.

ERP studies show strong support for deficits in auditory perceptual processing and specific language processing in dyslexic participants. A majority of these differences are restricted to demanding tasks either in terms of stimulus discriminability or response. However not all ERP differences between dyslexic and control participants can be explained by perceptual deficits. Differences in P300 and N400 components are difficult to attribute to purely perceptual processes, especially in the absence of earlier N1, P1 or P2 differences. However, it is important to note that reduced or delayed early components (e.g. N1, P1) may induce carry over effects to subsequent components. This is especially true of latency differences (Breznitz & Misra, 2003).

Overall, ERP and behavioural studies draw attention to the necessity to control for co-morbid disorders when attempting to locate impairments causal to developmental dyslexia.

### 3.4 Thesis Scope

Strong evidence for the presence of a phonological processing deficit in the majority of developmental dyslexic children and adults is evident from the literature review presented in the preceding Chapters (1 - 3). However, it is also evident that a phonological processing deficit is not the only processing limitation likely to result in the literacy impairments observed in dyslexic children and adults. Furthermore, it is

clear that little is understood about the specificity of the phonological processing deficit to phonological awareness and its relationship to phonological representations, working memory and attentional processes (Ramus, 2001). ERPs can be used to examine differences in perceptual and attentional processes over time and are therefore suitable to investigate the contribution of these processes to the literacy impairments observed in dyslexia. The following experimental chapters will examine the question of phonological processing deficits in developmental dyslexia, the specificity of this processing deficit and also the importance of attentional limitations to the presentation of phonological processing deficits.

In chapter 4 ERP changes between dyslexic and control participants are examined to the detection of initial phoneme changes in words and pseudo-words when attention is focused on a different task (Chapter 4). Subsequently, ERP and behavioural differences were examined between dyslexic adults and controls when attention is focused on the detection of the same wide phonetic discrimination or an additional narrow phonetic discrimination (Chapter 5). After establishing some importance of focused attention in the phonological processing deficits observed in dyslexia as indexed by ERP changes, ERP and behavioural differences in phonological tasks requiring greater attention demands than simple phoneme detection (phoneme deletion) were used to probe for possible attentional deficits with a matched non-linguistic auditory task requiring similar attentional demands (Chapter 7). An attempt is also made to examine the presence of a deficit in implicit phonological processing in dyslexic adults by comparing ERP components known to index phoneme expectancy in dyslexic adults and controls for phonotactically plausible and implausible distracters in a phoneme deletion task (Chapter 6). Finally,

ERP and behavioural measures are used to examine the presence of an amodal attentional deficit in dyslexic adults (Chapter 8).

The crucial transition in literacy development involves a step from implicit to explicit control of the phonemic units of language. (Lundberg, 1998, p.155)

# Chapter 4

### Phoneme awareness: Attention to phoneme changes

# 4.1 Introduction

Behavioural measures of verbal short-term memory, phoneme awareness, rapid naming, non-word reading, and speech perception have all been utilized to investigate phonological processing deficits in developmental dyslexia (see Chapter 2). To some extent these tasks are divided on whether they tax the conscious segmentation of phonemes (phonological awareness) or unconscious (implicit) processing of phoneme changes (Morais, Cary, Alegria, & Bertelson, 1979; Morais & Kolinsky, 1994).

Although awareness of the phonological units of speech is seemingly not required for speech perception and comprehension (Fowler, 1991), it correlates with reading skill and predicts the later reading abilities of pre-literate children (Bradley & Bryant, 1978; Mann & Liberman, 1984; Muter, Hulme, Snowling, & Taylor, 1998; Pennington, Van Orden, Smith, Green, & Haith, 1990; Wood & Terrell, 1998). One measure of phoneme awareness that has been shown to predict the reading ability of young children is the identification of initial phoneme oddballs in a series of alliterated words (Bradley & Bryant, 1983).

The classical P300 ERP component is a reliable index of conscious attentional shifts observed when infrequent stimuli (deviants) are detected within a series of identical frequent stimuli (standards, Donchin, 1981; Polich, 1986; Soltani & Knight, 2000). Completely unexpected stimuli different from standards and deviants within an oddball stream ('novel' task-irrelevant stimuli) elicit a somewhat different P300 peaking slightly earlier over fronto-central regions ('novelty P300', Soltani & Knight, 2000). Studies of classical and 'novelty' P300s have led to the differentiation of two subcomponents within the P3 wave: (a) The P3a more visible over fronto-central electrodes and thought to index shifts of attention (Escera, Alho, Winkler, & Näätänen, 1998); and (b) the P3b more visible over centro-parietal electrodes and thought to index target detection and working memory updating (Polich & Kok, 1995). In the auditory modality, P3a/P3b complexes have been studied using pure tone oddballs (e.g. Donchin, 1981), phonological oddballs (e.g. Erez & Pratt, 1992; e.g. Newman, Connolly, Service, & McIvor, 2003), and lexical oddballs (e.g. Polich & Donchin, 1988; Tainturier, Tamminenn, & Thierry, 2005). Importantly, the P3 wave in these tasks is not modulated by response preparation, making it possible to measure ERP responses to an implicit and orthogonal oddball discrimination (Ito & Cacioppo, 2000).

It is therefore possible to use the P3 wave to index phoneme awareness by manipulating the local probability of a phoneme within a series of words. P300 investigations in dyslexic individuals have shown quantitative differences (e.g. a delayed and/or reduced P3b Erez & Pratt, 1992; e.g. a delayed and/or reduced P3b Mazzotta & Gallai, 1992) and slightly enlarged P3a to task irrelevant novel sounds (Rüsseler, Kowalczuk, Johannes, Wieringa, & Münte, 2002), but no qualitative

differences have yet been reported, possibly because language-specific stimuli are rarely used.

Here, we engaged dyslexic adults and matched controls in a lexical decision task while the phonological probability of the words' initial phoneme was varied: Eighty percent of the stimuli were alliterated (standards) and twenty percent were phonological deviants (i.e. started with another phoneme). We hypothesised that deviant as compared with standard stimuli would induce a reorientation of attention in normal readers resulting in a P3a modulation. However, since phoneme awareness is deficient in individuals with developmental dyslexia, we expected the P3a to be significantly reduced or cancelled.

## 4.2 Methods

### 4.2.1 Participants

Twenty-four students (12 dyslexic and 12 controls) from the University of Wales Bangor research panel participated. The twelve dyslexic adults (6 males, 6 females, aged 18-29, mean 21.4  $\pm$ 3.8, one left-handed) were selected on the basis of an educational psychologists assessment focusing predominantly on discrepancies between verbal and non-verbal performance (Turner, 1997). There was no record of reading difficulties in the control group (6 males, 6 females, aged 19-30, mean 21.3  $\pm$ 3.2, all right-handed), which was matched to the dyslexic group for mean age and level of education. Individuals were further assessed on three sub-tests of the dyslexia adult screening test (DAST, Nicolson & Fawcett, 1997).

### 4.2.2 Stimuli

Stimuli were 352 nouns pronounced by a female speaker with natural prosody and selected from the CELEX database (Baayen, Piepenbrock, & Gulikers, 1995). The words were controlled for duration (phoneme length: 4 to 7 phonemes) and lexical frequency (CobLog greater than 0.8) known to affect the amplitude of P300 responses (Polich & Donchin, 1988, see Table 4.1). Eight sets of words were prepared: 4 sets of 70 nouns starting with the phonemes /b/, /k/, /p/ or /r/ (standards) and 4 sets of 18 nouns starting with the phonemes /n/, /m/, /l/, and /g/ (deviants), see examples in Table 4.2 (also see full stimulus list in Appendix i). An equal number of pseudo-words were derived from the words by changing their medial consonant (third or fourth phoneme), for example 'packet' [pækɛt] became 'pamet' [pæmɛt].

Lexical Frequency (CobLog)		Duration (ms)		
Standards	Deviants	Standards	Deviants	
1.34 (±0.44)	1.40 (±0.39)	571 (±112)	554 (±108)	

Table 4.1 - Mean values and standard deviations in parenthesis for lexical frequency and duration across all blocks.

	Standards	Deviants	
/r/ and /g/	rabbit	gallon	
/b/ and /n/	barrel	nylon	
/k/ and /m/	cottage	missile	
/p/ and /l/	packet	lemon	

Table 4.2 - Example words for each block.

### 4.2.3 Procedure

Participants were presented with 4 blocks each comprising 140 alliterated words and pseudo-words and 35 deviant words and pseudo-words starting with a highly contrasting phoneme (/b/, /k/, /p/ and /r/ standards paired with /n/, /m/, /l/ and /g/ deviants, respectively). Trial order was quasi-randomised so that there was no more than one deviant and no less than two standards presented in succession. Participants were asked to press keyboard keys set under their left and right index fingers according to whether they heard a word or a pseudo-word (lexical decision). Response side and block order were fully counterbalanced across participants.

### 4.2.4 EEG Recording and Processing

Continuous recordings sampled at 1 KHz and filtered bandpass on-line between 0.1 Hz and 40 Hz were measured from 64 Ag/AgCl electrodes referenced to Cz, before being digitally re-filtered (low pass, 35 Hz, 48dB/Oct). Impedances were kept below 9 K $\Omega$ . Eye blink artefacts were mathematically corrected and recordings were visually inspected for the rejection of any remaining artefacts before being cut into 1100 ms epochs. Baseline correction was applied relative to the 100 ms prestimulus activity. Individual ERPs were re-referenced to the global average reference and grand-averages for each condition were computed.

#### 4.2.5 Statistical Analysis

Electrodes T7 and T8 were not included in the statistical analysis due to excessive artefacts. Search intervals for ERP peaks were identified on the basis of major modulations of the mean global field power (MGFP (Picton et al., 2000)): 70 to 140 ms for the N1, 140 to 240 ms for the P2, 240 to 300 ms for the N2, 300 to 340 ms for the P3. Mean signal amplitudes were analyzed in 9 scalp regions defined by laterality (left, central, right) and anteriority (frontal, central, parietal) using a 2 x 2 x 9 within- x 2 between-subject MANOVA (Picton et al., 2000), Figure 4.1. Within-subject factors were: Lexicality (word, pseudo-word), Oddity (standard, deviant), and Region (9 levels). Interactions involving the Region factor were validated using vector normalisation (McCarthy & Wood, 1985).



Figure 4.1 – 9 scalp regions used for statistical analysis.

## 4.3 Results

## 4.3.1 Cognitive Assessment

Control participants performed significantly better than dyslexic adults on both the one-minute reading (control adults:  $100 \pm 11$  and dyslexic adults:  $72 \pm 22$ , F[1,20] = 14.56, p < 0.01) and the two-minute spelling tests (control adults:  $32 \pm 3$ , dyslexic adults:  $24 \pm 4$ , F[1,20] = 24.64, p < 0.001), but not on the non-verbal reasoning test (F[1,20] = 0.01, p = 0.913).

### 4.3.1 Behavioural Performance

Error rates were significantly lower (F[1,22] = 9.08, p <.01) in controls (mean =  $4.3 \pm 2.5\%$ ) than dyslexic adults (mean =  $11.9 \pm 10.3\%$ , see Fig. 2). The performance of both groups was significantly better (F[1,22] =18.80, p <.001) for deviants ( $3.1 \pm 2\%$  errors) than standards ( $5.5 \pm 2.4\%$  errors). However, a significant lexicality by group interaction (F[1,22] = 5.05, p < .05), indicated that while control participants did not differ at identifying words ( $4.8 \pm 2.5\%$  errors) and pseudo-words ( $3.8 \pm 2.5\%$  errors), dyslexic participants were significantly better at identifying words than pseudo-words ( $9.2 \pm 6\%$  errors for words and  $14.7 \pm 12.9\%$  errors for pseudo-words).



Figure 4.2 – Behavioural results. The bars represent reaction times and the bullets depict error rates. Error bars index the standard deviation in all cases.

Control reaction times (RTs) measured from stimulus onset (981 ±108 ms) were significantly shorter (F[1,22] = 8.55, p <.01) overall than dyslexic adult RTs (1132 ±156 ms). Both groups responded faster (F[1,22] = 7.47, p <.05) to deviants (1052 ±153 ms) than standards (1062 ±155 ms), and faster (F[1,22] = 38.58, p < .001) to words (1016 ±133 ms) than pseudo-words (1098 ±162 ms). No interactions were found.

## 4.3.2 Electrophysiological Results

Words and pseudo-words elicited an N1-P2-N2 peak sequence in all participants. The N1 peaked around 100 ms, the P2 around 190 ms and the N2 around 290 ms on average. None of these peaks were significantly influenced by experimental factors.

In the P300 range, only an interaction between Oddity, Group and Region was significant after normalisation (F[8,15] = 2.90, p < .05). Post-hoc paired *t*-tests showed that the ERP mean amplitudes were significantly more positive for deviants than standards over the right central region in controls (t[11] = +3.14, p <.05, one-tailed, Bonferroni corrected for multiple comparisons) but not in dyslexic adults (Fig. 3; also see Appendix vi, Fig. 1 for individual performance). This effect was maximal at electrode C6 310 ms after stimulus onset. Furthermore, individual peak amplitudes of the P300 effect over the right central region correlated significantly (r = +.40, n = 22, p < .05, one-tailed) with individual reading scores on the DAST subtest (Fig. 4).



Figure 4.3 – ERPs elicited by standard and deviant stimuli in control participants and matched dyslexic adults. The shaded areas indicate the time window of the P300 peak. Note that no P300 modulation was visible in dyslexic individuals.



Figure 4.4 – Correlation between P300 effect and individual scores on the DAST reading subtest for 22 participants. The data from one participant in each group had to be discarded for technical reasons.

## 4.4 Discussion

Consistent with previous findings, dyslexic adults made more errors and were slower at making lexical decisions than matched controls (Nicolson & Fawcett, 1994). This has previously been interpreted as a deficit in lexical access (Nicolson & Fawcett, 1994). However, as the pseudo-words present in our study deviated from real words by only a single medial phoneme, it is difficult to discriminate between a deficiency in lexical access and a deficiency in the phonological representation of lexical entries (Snowling & Hulme, 1994).

Although controls performed equally well in classifying words and pseudowords, dyslexic participants were significantly better at identifying words. This suggests that in the dyslexic participants, lexical mechanisms were more impaired when an exhaustive search of lexical representations was required, rather than direct access to known words. This is supported by the poorer performance of Spanishspeaking dyslexic children in making lexical decisions to low frequency compared with high frequency words (Jimenez Gonzalez & Hernandez Valle, 2000).

The faster reaction times for words relative to non-words have been shown repeatedly in normal readers (Praamstra & Stegeman, 1993) and dyslexic individuals (Nicolson & Fawcett, 1994). Such differences are usually regarded as reflecting a process of exhaustive search for a non-existent lexical representation and subsequent exploration of semantic memory.

As expected, phonological probability induced a deflection in the P300 range in control participants. Unlike the classical P3a (Escera, Alho, Winkler, & Näätänen, 1998), which normally has a central distribution, the modulation observed in this study was right-lateralised and small in amplitude. Nevertheless the modulation observed in this study bore greater resemblance to the topography of the P3a recorded to auditory task irrelevant stimuli than the classical P300 (P3b; Escera, Alho, Winkler, & Näätänen, 1998; Rüsseler, Kowalczuk, Johannes, Wieringa, & Münte, 2002).

Although participants were not explicitly instructed about the phonological manipulation, a change in the first phoneme of words and pseudo-words induced a phonological 'surprise'. Whereas the classical P3b effect has been proposed to index conscious attentional shifts to task relevant stimuli (Donchin, 1981; Polich, 1986), the P3a is observed when attention is captured by an unexpected task irrelevant stimulus change (Escera, Alho, Winkler, & Näätänen, 1998; Soltani & Knight, 2000). The

absence of the P3a modulation in dyslexic adults suggests that their attention was not diverted from the lexical decision task by the presence of phonological deviants.

Importantly, despite the absence of a P3a modulation in the dyslexic group, dyslexic participants responded significantly faster to deviants than to standards. This suggests that although they did not shift their attention toward phonological cues during the experiment, they implicitly processed the difference in the first phoneme to some extent. This tends to support a deficit in phoneme awareness rather than implicit phoneme discrimination abilities in dyslexic individuals.

The significant correlation between the P3 effect and individual reading scores further supports a relationship between phoneme awareness and reading skill.

The absence of a marker for a shift in attention to phonological variations in dyslexic participants needs to be explained. It may be the case that dyslexic adults have normal implicit phoneme processing abilities while their capacity to attend to phonological cues that are not directly relevant for the current task are limited. Such is the case in normal reading where developing readers will need to focus on the phonological subcomponents of words to establish phoneme to grapheme rules, although shifting attention to these changes is not required for comprehension of spoken language. Alternatively, it is possible that general attentional resources of dyslexic adults are insufficient to allow good performance in the lexical decision task while, at the same time, noticing phonological variations. It is therefore possible that the absence of a P3 effect relating to phoneme change detection is due to a non-specific attentional deficit rather than one specific to phonological processing. Such general attention deficits have been asserted previously on the basis of differences in the novelty P3 (P3a) to task irrelevant tone stimuli in dyslexic participants (Rüsseler,

Kowalczuk, Johannes, Wieringa, & Münte, 2002). However, other authors' have proposed that significant P300 modulations in dyslexic individuals may be limited to participants that show evidence of co-morbid attention deficit disorder (ADD, \Duncan, 1994).

Further investigation will be required to dissociate the presence of an attention deficit specific to phonological cues (phoneme awareness) from one that is non-specific, but independent of ADD symptoms.

## 4.5 Conclusion

P3a amplitude modulations observed to task irrelevant phonological variations correlate with reading performance in the same way as behavioural performance on focused oddball detection tasks do in young children (Bradley & Bryant, 1978). The results of this study are consistent with the presence of a phoneme awareness deficit in dyslexic adults.

# Chapter 5

### **Processing of Attended Phoneme Changes**

### 5.1 Introduction

Developmental dyslexia is associated with impaired performance on phonological awareness tasks which can be identified in the early school years (Betourne & Friel-Patti, 2003) and into adulthood (Bruck, 1992). Some phonological training programs have been shown to increase reading accuracy, although reading fluency appears to be less prone to improvement (Torgesen et al., 2001). Nevertheless, behavioural differences in phonological awareness tasks have been demonstrated in high performing dyslexic adults (Felton, Naylor, & Wood, 1990; Pennington, Van Orden, Smith, Green, & Haith, 1990), even those who are successfully pursuing university studies (Bone, Cirino, Morris, & Morris, 2002; Hatcher, Snowling, & Griffiths, 2002).

In the previous study (Chapter 4) we observed that the P3a elicited by phonological oddballs in adult participants performing a lexical decision task (LDT) was absent in university dyslexic adults. Since the participants were not explicitly instructed about the phonological oddball manipulation, but rather focused on the LDT, we speculated that the P3a observed in controls indexed spontaneous attentional shifts towards deviant phonemes (see for instance Escera, Alho, Winkler, & Näätänen, 1998). Thus, the absence of a P3a modulation in dyslexic participants indicated that they were either (a) not aware of the phonological difference between standards and deviants despite having the resources to attend to them, or (b) not able

to free up attentional resources required by the LDT to enable detection of the phoneme change.

In order to discriminate between these two hypotheses, we used the same phonological oddball context as before, but the phonological differences were placed directly in the focus of attention by requesting phonological decisions rather than lexical ones. Two different phonological contrasts -narrow, /b/-/p/ and wide, /r/-/g/- were used to test for possible effects of phonemic distance. Voicing was considered a critical phonemic feature as normal adults find it harder to distinguish phonemes that vary only in voicing than in other articulatory characteristics (Miller & Nicely, 1955), with recent evidence suggesting that voicing poses even greater difficulty for dyslexic children (Maassen, Groenen, Crul, Assman-Hulsmans, & Gabreëls, 2001). In line with the previous study, it was hypothesized that a specific phoneme awareness deficit would result in a significant reduction of the P3 modulation when attention is paid to phoneme oddballs directly. However, a modulation of the P3b was expected rather than the P3a since the phonological oddball was the target (rather than a distracter). Alternatively, indistinguishable performance and P3b response to phoneme oddballs in the focus of attention would suggest an important role of attention in the manifestation of the phonological deficit. In addition, a larger P3b modulation was expected for the /r/-/g/ than the /b/-/p/ phonological contrast in both groups, since discrimination difficulty is known to influence the P3b amplitude (Kok, 2001).

## 5.2 Materials and Methods

### 5.2.1 Participants

Twelve developmental dyslexic adults (mean age  $20 \pm 1$  year, 4 males) and 12 control adults (mean age  $19 \pm 1$  year, 4 males) took part in the experiment which was approved by the University of Wales Bangor ethics committee. All participants were right-handed native English speakers. Dyslexic volunteers were referred by the Bangor Dyslexia Unit. All had a record of reading difficulties and were diagnosed dyslexic on the basis of a battery of standardised tests that focused on the discrepancy between verbal and nonverbal performance (Turner, 1997). Participants matched for level of education were administered an additional dedicated battery of subtests to assess differences in reading and spelling. Subtests were taken from the Dyslexia Adult Screening Test (DAST, Nicolson & Fawcett, 1997), WAIS-III (Wechsler, 1997) and Wide Range Achievement Test (WRAT-3; Wilkinson, 1993). In addition, the Barkley current symptom scale (Barkley & Murphy, 1998) was used as a selfreport measure of Attention Deficit Hyperactivity Disorder (ADHD) symptoms to control for potential co-morbidity effects.

### 5.2.2 Stimuli

The stimuli were 175 words selected from the CELEX database (Baayen, Piepenbrock, & Gulikers, 1995) and 175 pseudo-words pronounced by a female speaker with natural prosody and digitized at 44.1 KHz (see Table 5.1; selected from the stimuli used in Exp 1, see Chapter 4 and Appendix ii for full stimulus list). Stimulus duration was 562 ±139 ms on average. Words were controlled for lexical

frequency (CobLog frequency greater than 0.8) and length (4 to 7 phonemes). Two initial phoneme contrasts were used: /r/ versus /g/ (wide contrast), and /b/ versus /p/ (narrow contrast). /r/ and /g/ vary in place of articulation (alveolar / velar) and manner of articulation (approximant / plosive), but not voicing (both are voiced). /p/ and /b/ have the same place (bilabial) and manner (plosive) of articulation, but have different voicing (unvoiced / voiced). The pseudo-words were derived from the words by changing their medial consonant (3rd or 4th phoneme), for example 'packet' [pækɛt] became 'pamet' [pæmɛt].

Standards		Deviants			
Frequency	Example	Frequency	Example		
1.17 ± 0.38	basin bafin	1.30 ± 0.07	packet pamet		
1.37 ± 0.41	rabbit raddit	1.18 ± 0.32	gallon gatton		

The CELEX Lexical Database (Baayen, Piepenbrock, & Gulikers, 1995)

Table 5.1 – Example words and pseudo-words for phonological contrasts (/b/-/p/, first row and /r/-/g/, second row) with mean lexical frequency (CobLog<sup>1</sup>). Pseudo-words are italicized.

### 5.2.3 Design and Procedure

The oddball manipulation was based on the initial phoneme of each stimulus: Standards (80%) started with /r/ or /b/ and deviants (20%) started with /g/ or /p/, respectively. Stimuli were presented to participants through inner auricular earphones (Etymotic<sup>TM</sup> Research, Illinois, USA) at the start of an 800 ms response window. Participants were asked to press a keyboard button with their right index finger on each occurrence of the deviant (low probability initial phoneme). Stimulus onset asynchrony was held constant at 1400 ms, which was the maximum response time beyond which a trial was deemed an error. False alarms were analysed separately. Participants were asked to fixate on a red dot in front of them to minimise eye blinks and head movements. Block order was counterbalanced across participants.

#### 5.2.4 EEG Recording and Processing

EEG recordings were digitized at 1 kHz from 32 Ag/AgCl electrodes conforming to the extended international 10-20 convention and referenced to Cz. Bipolar recordings were made from electrodes set above and below the left eye. Continuous recordings were band pass filtered on-line between 0.01 and 200 Hz before being digitally re-filtered off-line (zero phase shift low pass 35 Hz, slope = 48 dB/Oct). Eye blinks were mathematically corrected when the standard deviation of the blink model was below 0.005 (Scan 4.2; Neuroscan Inc., Texas, USA). Signals were then sliced into 1.1 s epochs, starting 100 ms before and ending 1000 ms after stimulus onset. Baseline correction was performed in reference to pre-stimulus activity. Individual averages were re-referenced to the global field power (GFP) produced across the scalp (average reference) before grand averages were calculated for each condition.

#### 5.2.5 Statistical Analysis

Main ERP components were identified based on their typical topography, deflection and latency. Windows of analysis for each component were defined on the basis of the mean global field power (MGFP) across conditions and groups (Picton et al., 2000): 70 to 140 ms for the N1, 140 to 240 ms for the P2, 240 to 320 ms for the N2, 320 to 380 ms for the P3a, and 450 to 700 ms for the P3b. Peak detection was time-locked to the electrode of maximal amplitude for each component: Cz for the N1 and P2, Fz for the N2 and P3a, and Pz for the P3b. In each case, mean amplitudes were measured at three contiguous electrodes chosen a priori, based on the known region of maximum sensitivity for each component (Picton et al., 2000): C3, Cz, C4 for the N1 and P2; FC1, Fz, FC2 for the N2 and P3a; and CP1, Pz, CP2 for the P3b. Mean amplitudes were submitted to a 2 x 2 x 3 within- x 2 between- subject repeated measures ANOVA. Within-subject factors were: Oddity (standard, deviant), phonological contrast (/b/-/p/ or /r/-/g/), and electrode (three in all cases). The between-subject factor was group (control, dyslexic). Since no prediction regarding differences in peak latencies were made, and since no significant group effect or interaction involving the group factor were found on the latency of the P3a and P3b, latency analyses are not reported. A Greenhouse-Geisser correction was applied to electrode main effects and interactions where appropriate (Greenhouse & Geisser, 1959). Interactions involving the electrode factor were validated using vector normalisation (McCarthy & Wood, 1985). Unless otherwise specified, only significant main effects and interactions surviving normalisation (p < .05) are reported.

### 5.3 Results

### 5.3.1 Cognitive Assessment

Dyslexic and control participants did not differ in their measures of nonverbal performance or ADHD symptoms (Table 5.2; also see Appendix v, Table 1 for

individual performance). However, dyslexic adults performed significantly more poorly than controls in the two reading subtests and in the two spelling subtests used. No participant fell below one standard deviation (SD) of the normal population on the WRAT-3 spelling or reading scores.

	Control		Dyslexic		
	М	SD	м	SD	P-value
DAST Reading (words / min)	101	10	88	17	<.05
DAST Spelling (words / 2 min <sup>1</sup> )	35	2	28	4	< .001
DAST Non-verbal (range 0 - 8)	6	2	6	2	NS
WRAT Reading <sup>2</sup>	110	5	103	5	< .01
WRAT Spelling <sup>2</sup>	107	5	94	9	<.001
WAIS Matrix Reasoning (range 0 – 26)	19	3	20	4	NS
WAIS Digit Span (range 0 - 30)	17	4	16	4	NS
ADHD Symptom Scale					
Inattention (range 0 - 9)	3	2	3	2	NS
Hyperactivity (range 0 -9)	2	2	3	2	NS

<sup>1</sup> Based on the scoring criteria for this test, values are equal to the number of words spelt

correctly in 2 minutes plus 8 additional points

<sup>2</sup> Standard Score

Table 5.2 - Cognitive Assessment. Means (M) and standard deviations (SD) are shown for each score on the cognitive subtests. P-values are given for each significant effect based on a between subjects ANOVA.

### **5.3.2 Behavioural Results**

A repeated measures ANOVA failed to reveal any significant differences in performance between the groups (Fig. 5.1a; also see Appendix vi, Fig.2 for individual performance). The only significant effect was a main effect of phonological contrast on reaction times (F[1,22] = 5.15, p < .05), such that responses to the /r/-/g/ contrast (mean =  $752 \pm 126$  ms) were faster than those to the /b/-/p/ contrast (mean =  $806 \pm 170$  ms) in both groups (errors being dismissed).

False alarms were Arcsine transformed due to their low rate and submitted to a repeated measured ANOVA (Howel, 1997). Both the control and dyslexic participants made significantly more false-alarm responses (F[1,22] = 6.43, p < .05) to the narrow contrast (/b/-/p/) than the wide contrast (/r/-/g/; Fig 5.1b).

The number of misses was low in both groups:  $3 \pm 3$  and  $4 \pm 3$  misses for the narrow and wide phonological contrasts, respectively, in controls, and  $3 \pm 2$  and  $2 \pm 2$  misses for the narrow and wide phonological contrasts, respectively, in dyslexics. The miss rates were too low to show any significant difference between groups.



Figure 5.1 – Behavioural results. (a) Bars depict reaction times in controls (left) and dyslexic adults (right) for the narrow phonological contrast in which the deviant /p/ was the target and the wide phonological contrast in which the deviant /g/ was the target. Circles depict miss rates. (b) False alarms plot. Error bars indicate standard errors in all cases.

### 5.3.3 ERP results

Five ERP components were observed in both groups: N1, P2, N2, P3a and P3b. Grand average waveforms recorded at 9 electrodes in the two groups are shown in Fig. 5.2.





Contraction 103

Figure 5.2 – Grand average ERPs elicited by standard initial phonemes (thin lines) and deviant initial phonemes (thick lines) in (a) controls and (b) dyslexic adults. Shaded boxes depict the interval of analysis of the P3b.

The N1 was maximal at Cz and peaked at  $104 \pm 10$  ms on average. There was a significant phonological contrast x group interaction on the amplitude of the N1 (F[1,22] = 4.92, p < .05, see Figure 5.3). Control participants showed a increased N1 for the /b/-/p/ initial phoneme pair as compared to the /r/-/g/ pair (t[11] = -2.52, p < .05) which was not observed in dyslexic adults (t[11] = .34, p > .1). No other interaction or main effect on N1 amplitude was found.



Figure 5.3 – Grand average ERPs elicited by the /b/-/p/ (doted lines) and the /r/-/g/ (solid lines) initial phoneme pairings in the controls (black) and dyslexic adults (grey) at Cz. The N1 was different between phonological pairings in the control group but not in the dyslexic group.

The P2 was maximal at Cz and peaked at  $192 \pm 16$  ms on average. There was an oddity x phonological contrast interaction on P2 amplitudes in both dyslexic and control adults (F(1,22) = 21.92, p < .001, see Figure 5.4). The P2 was smaller for /p/ than /b/ (t[23] = 3.96, p < .01) and for /r/ than /g/ (t[23] = -2.16, p < .05). No other effects or interactions on P2 amplitude were found.



Figure 5.4 – Grand average ERPs elicited by the four initial phonemes /r/ (solid black line), /g/ (doted black line), /b/ (solid grey line) and /p/ (doted grey line) averaged over participant groups at Cz. The P2 was significantly larger for /b/ and /g/ than /r/ and /p/.

The N2 was maximal at Fz and peaked at  $289 \pm 19$  ms on average. A significant main effect of initial phoneme oddity was observed on the N2 (F[1,22] = 4.54, p < .05, see Figure 5.5). Deviant initial phonemes elicited a greater N2 than standard initial phonemes (t[23] = 2.16, p < .05). There was no group main effect or group interactions for this component.



Figure 5.5 – Grand average ERPs elicited by standard initial phonemes /r/ and /b/ (solid line) and deviant initial phonemes /p/ and /g/ (doted line) averaged over participant groups at Fz. The N2 was significantly larger for deviants than standards.

The P3a peak was most visible at fronto-central sites and peaked at  $352 \pm 19$  ms on average. It was not significantly modulated by any of the experimental factors and was not different between groups.

The P3b was maximal at Pz and peaked at 583  $\pm$ 73 ms on average (Fig. 5.2 and 5.6). It was significantly modulated by phoneme oddity (F[1,22] = 49.64, p < .001). In both groups, deviant phonemes /p/ and /g/ elicited significantly greater amplitudes than standards /b/ and /r/ (see Appendix vi, Fig.2 for individual performance). There was no significant interaction between oddity and phonological contrast. However, the modulation of the P3b (deviant – standard) tended to be proportional to the phonemic distance (Fig. 6). The size of the P3b effect was indeed larger for the /r/-/g/ pair (Cohen's *d* = 1.8) than for the /p/-/b/ pair (Cohen's *d* = 1.0), using the conservative effect size calculation for repeated measures designs suggested by Dunlop *et al.* (Dunlop, Cortina, Vaslow, & Burke, 1996). No correlation between mean amplitudes and performance in the verbal subtests of the cognitive assessment were found for any of the ERP components observed.



Figure 5.6 – Grand average waveforms in the four experimental conditions averaged across groups over the centroparietal scalp (linear derivation of CP1, CP2 and Pz). Note that the P3b (shaded box) effect size (deviant – standard) tended to be greater for the narrow phonological contrast (grey lines) than for the wide phonological contrast (black lines).

### 5.4 Discussion

Control and dyslexic adults participating in this experiment had normal and indistinguishable performance in the nonverbal tests (Table 5.2). Classically, a difference in digit span is found between large groups of dyslexic and control adults (e.g. Hatcher, Snowling, & Griffiths, 2002). However, some studies fail to find differences in forward digit span for smaller groups of dyslexic adults (Helenius et al., 2002). No differences in digit span performance were found between control and
dyslexic adults in the present study and the variability in performance was similar across both groups. The absence of any differences may however relate to the use of compensation strategies, which have been identified in children, and which university students are likely more proficient at identifying and using (Helland & Asbjornsen, 2004). In addition, the reading and spelling performance of the dyslexic participants remained within one standard deviation (SD) of the normal populations' performance. Such a level of performance has been reported before for dyslexic adults with this level of education (Griffiths, Hill, Bailey, & Snowling, 2003; Hatcher, Snowling, & Griffiths, 2002). Nevertheless, dyslexic participants showed a clear impairment in reading and spelling compared with matched controls.

Dyslexic participants' performance did not differ from that of controls in error rates, reaction times or number of false alarms. Both the dyslexic and control participants responded faster to the wide phonological contrast and made more falsealarms on the narrow contrast. This suggests that both the dyslexic and control participants found it harder to identify oddball initial phonemes correctly when they were presented with standard initial phonemes that varied only in voicing from the oddballs, than when they varied in both place and manner of articulation. There was no difference between groups in this behavioural pattern. Although some authors have shown a difference between dyslexic and control participants performance for narrow phonological contrasts on artificial continua (Manis et al., 1997), this reduction in discrimination ability does not seem to carry over to the identification of phonemes in natural speech, at least not when the stimuli are highly discriminable by the controls (Serniclaes & Sprenger-Charolles, 2003).

The N1 mean amplitude was significantly greater for /b/ and /p/ than /r/ and /g/ initial phonemes in controls only. The less discriminative N1 observed in dyslexic

participants did not however correlate in amplitude with any of the cognitive assessment measures. The N1 is modulated by the unconscious focusing of attention as well as perceptual changes in the stimulus (Davis & Zerlin, 1966; Hillyard, Hink, Schwent, & Picton, 1973). The attentional focus of this task was consistent across the /b/-/p/ and /r/-/g/ conditions, with the same active response required in both. Under these conditions, modulations of the N1 are more likely to index low-level perceptual processing capacity (Leppanen & Lyytinen, 1997). For example, Pinkerton et al. (1989) observed a smaller N1 in poor readers during a passive tone listening task, the amplitude of which correlated with performance IQ, comprehension, reading and spelling measures. However, using similar tasks, others have observed no differences in the N1 between dyslexic and control individuals (Yingling, Galin, Fein, Peltzman, & Davenport, 1986). In contrast to simple tones, phonemes are complex acoustic signals incorporating several frequency bands and modulations. Therefore, N1 differences arising in the context of pure tone passive listening may not be a powerful test of higher order auditory processing involved in phonological awareness. Nevertheless, the lack of difference in performance between dyslexic and control adults shown here tends to discard any significant relationship between the N1 difference and phoneme identification per se.

The amplitude of the P2 was greater for /b/ and /g/ than the /r/ and /p/ initial phonemes. The P2 has been shown to be modulated by short term memory demands (Conley, Michalewski, & Starr, 1999), and is also suggested to vary with acoustic differences between phonemes (Newman, Connolly, Service, & McIvor, 2003). In this study the difference in the P2 is likely to represent the greater processing demands of /b/ and /g/ phonemes which have minimal perceptual cues for identification (Liberman, Cooper, Shankweiler, & Studdert-Kennedy, 1967). When

long, voice onset time (VOT) provides a distinct cue for the identification of phonemes (so-called voiceless phonemes). However, in the case of English, voiced stop consonants such as /b/ and /g/ have little if any voicing lag (short VOT). Phonemes /b/ and /g/ are therefore less perceptually salient than /p/ and /r/ and may require more processing. This effect possibly relates to the P2 modulation reported by Newman *et al.* (2003) who engaged participants in a phoneme deletion task. The task was to decide whether the second word of a pair (e.g., 'lap') was the first word (e.g., 'clap') devoid of its first phoneme. Newman *et al.* (2003) observed that the P2 was significantly larger for targets (correct phoneme deletion) than foils (irrelevant words). They suggested that this modulation reflected changes in the acoustic features of the different initial phonemes presented across conditions.

The N2 was significantly more pronounced for phonological deviants than standards. This effect can be attributed to a mismatch negativity (Näätänen & Alho, 1995) indicating automatic detection of phonological oddballs within the alliterated stream of words (Celsis et al., 1999). Similar effects have been described previously in experiments manipulating phonological expectancy in spoken sentences (J.F. Connolly & Phillips, 1994). Here, the N2 effect did not interact with group, suggesting that implicit phonological expectations were intact in dyslexic participants.

We found no significant P3a modulation in either group. Since participants' attention was fully dedicated to the initial phoneme of words, there is no reason why a P3a modulation indexing automatic detection of novel (task-irrelevant) events should be observed (Soltani & Knight, 2000). Interestingly, in Experiment 1 (Chapter 4), it is the P3a that was modulated by phoneme oddity in controls, probably because phonological oddballs constituted attention-grabbing stimuli outside the main focus of the task (Escera, Alho, Winkler, & Näätänen, 1998). Indeed, the task being a LDT

meant that the probability of the initial phoneme was irrelevant. As we speculated at the time, the absence of such a P3a modulation in the dyslexic adult group could indicate a failure to shift attention to phonological cues, possibly due to the high demands of the LDT.

A large P3b maximal at centroparietal sites was observed in dyslexic and control participants, consistent with the hypothesis that the phoneme oddball was efficiently detected by both groups (Polich & Kok, 1995; Soltani & Knight, 2000). The absence of any group differences in both the P3a and the P3b windows was congruent with the absence of differences in behavioural oddball task performance. In the previous study using one of the same wide phonological contrasts alliterated streams of words and pseudo-words, no P3a was observed in dyslexic adults when their attention was focused primarily on lexical decision rather than phonological oddballs. When the focus is on phonological processing, however, the P3b effects elicited by phonological oddballs in dyslexic and control adults are indistinguishable. Overall, the absence of ERP differences between the two groups in the present experiment may be a consequence of shifting the focus of attention to phonological monitoring.

Whereas we found a significant correlation between P3a amplitude and DAST reading score in the previous study, we failed to identify any correlation between either the P3a or the P3b amplitude and DAST reading score in the present study. The absence of correlation could be due to a limitation of P3b sensitivity, which reaches saturation level in tasks of low attentional demand (Duncan et al., 1994). Consistent with this view, demanding phoneme awareness tasks have been shown to correlate better with reading skill than simple phoneme discrimination (Yopp, 1988) or identification. It may therefore be the case that a more demanding phoneme

awareness task than the one used here, such as phoneme deletion or spoonerism judgment, would reveal differences between dyslexic and control individuals.

# 5.5 Conclusion

When phoneme identification is in the focus of attention, we show that P3b modulations elicited by phonological oddballs are identical in dyslexic and control participants, despite a clear difference in literacy skills between groups. This result stands in contrast to the previous study (Chapter 4) where a significant P3a modulation was observed in controls but not dyslexic adults when phonological oddballs were out of the attentional focus. Overall, these findings point to a major role of attentional resource allocation on phonological processing. Further research will determine whether phonological tasks with greater attentional demands allow differences between dyslexic and control adults to emerge.

# Chapter 6

# Phoneme Deletion in Dyslexic Adults

### 6.1 Introduction

Although dyslexic children are impaired for the detection of initial phoneme changes in an oddball paradigm (e.g. Bradley & Bryant, 1983), compensated dyslexic adults show little impairment on a similar task (Chapter 5). Varying the attentional focus of the task during exposure to a phonological oddball paradigm showed that the impairment of compensated dyslexic adults is limited to task irrelevant phoneme changes (e.g., during a lexical decision task; see Chapters 4 and 5). However, impaired performance has been repeatedly shown for compensated dyslexic adults on phoneme awareness tasks that require the manipulation of phonemic units in working memory: Phoneme deletion, phoneme insertion, spoonerism and piglatin constructions (e.g., Bruck, 1990; Ackerman, Dykman & Gardner, 1990; de Gelder & Vroomen, 1991; Pennington et al., 1990). Importantly, behavioural experiments suggest that these tasks vary in the attentional and memory demands they place on participants; higher and more demanding phoneme awareness tasks correlating better with reading skill (Yopp, 1988). Since phoneme deletion requires more attentional demands than phoneme detection, it is more likely to reveal subtle deficiencies in the phonological processing abilities of compensated dyslexic adults.

Segmentation and recognition of individual phonemes are necessary to perform both phoneme detection and phoneme deletion tasks, but phoneme deletion also requires manipulation (subtraction) of a phoneme and blending of the remaining phonemes into a new word. In addition, phoneme deletion tasks often require

subtraction of an initial phoneme from a consonant cluster located at the beginning of the word. Word initial consonant clusters form coherent phonological units called onsets, which are separated from the 'rime' of the word by the first vowel (V<sub>1</sub>; see Figure 6.1; Treiman, 1987; Treiman & Kessler, 1995). As such, consonant clusters are perceived as indivisible perceptual units in which phonemes are much harder to segment as compared to onset – rhyme segmentation (Stuart & Coltheart, 1988). The difficulty of segmenting the onset consonant cluster is also supported by the fact that children make more spelling errors for consonant clusters than individual consonants (Bruck & Treiman, 1990). Furthermore, reading and segmenting onset consonant clusters in non-words are particularly difficult tasks for dyslexic children (Morais, Cluytens, & Alegria, 1984; Snowling, 1981) who make a majority of spelling errors on the second consonant in a cluster (C<sub>2</sub>; Bruck & Treiman, 1990). More generally, performance on phoneme deletion tasks has been shown to discriminate discrepancy defined dyslexics from poor readers and predict the later reading ability of young children (Badian, 1993).



Figure 6.1 - Internal syllable structure

The phonological deficits observed in developmental dyslexia are not limited to phoneme awareness. Impairments in rapid automatised naming (RAN) in dyslexic individuals are consistent with underspecified phonological representations at the lexical level (Elbro, 1998), whereas impairments in pseudo-word reading are consistent with underspecified sub-lexical phonological representations. Therefore it is important to examine impairments in both lexical and sub-lexical phonological representations in dyslexia. Furthermore, it is plausible that phonological awareness deficits stem from the underspecificity of sub-lexical phonological representations. If this is the case, deficits in sub-lexical phonological processing (e.g. knowledge of phonotactic regularities) other than pseudo-word reading should be identifiable in dyslexic individuals.

Here we will use the P300 as a marker of attentional processing in a phoneme awareness task. In addition, the N200 component will be used as an index of implicit phonological processing. Classically, in ERP studies involving language stimuli, the N2 peaks between 200 and 300 ms after stimulus onset and has been shown to index phonological expectancy in various contexts (Celsis et al., 1999; Connolly & Phillips, 1994; van den Brink, Brown, & Hagoort, 2001).

Using a phoneme deletion task based on the oddball paradigm, four conditions were created. In one condition the second word of a pair (e.g., lane) was identical to the first word (e.g., plane) devoid of its initial phoneme (match, 25%). In the other three conditions the initial phoneme of the second word was not a match (mismatches, 75%). Mismatches were either a word in which the first phoneme could plausibly follow the initial phoneme of the prime word (e.g., rain; /pr/ is phonological plausible), a word in which the first phoneme could not plausibly follow the initial

phoneme of the prime word (e.g, cane; /bk/ is phonologically implausible) or a pseudo-word (e.g., hain).

Since the match condition was only presented 25% of the time, a P3 modulation was expected when participants detected the match trials. Our hypothesis was that dyslexic participants, if impaired for the awareness of phonemes in high attentional demands, would show a reduced P3 to match trials because they would be less aware of the phoneme deletion match between the second and first words of a pair. Furthermore, since the N2 component is modulated by implicit phonological expectancy, we also expected to see greater amplitudes for mismatch than match trials. If the N2 discriminates different levels of phonological expectancy in the mismatches, we would expect larger N2 amplitudes for phonologically implausible words than phonologically plausible ones. In terms of behavioral performance, phonologically implausible mismatches would be more easily dismissed as inappropriate, whereas phonologically plausible mismatches would be harder to discriminate from the matches. Finally, mismatch pseudo-words acted as a more direct measure of sub-lexical processes, where top-down lexical influences are by definition minimal.

The aim of this experiment was to (a) characterise the P300 effect in dyslexic individuals as compared to controls on a phoneme deletion task with higher attentional demands than our oddball initial phoneme detection task (chapter 5), and (b) examine the effect of phonotactic expectancy on the N2 component for dyslexic and control participants.

# 6.2 Materials and Methods

### **6.2.1** Participants

Twenty-four Native English undergraduate students consented to participate in this study. Twelve control adults (3 males and 9 females, mean age  $20 \pm 1$  year, one left handed) were recruited through the University of Wales, Bangor subject panel and 12 dyslexic adults (2 males and 10 females, mean age  $20 \pm 2$  years, all right handed) through the Bangor Dyslexia Unit. All the dyslexic adults selected had a history of reading difficulties and were diagnosed dyslexic on the basis of a battery of standardised tests that focused on the discrepancy between verbal and nonverbal performance (Turner, 1997). All the dyslexic participants showed good compensation of their deficits as shown by their admittance to an undergraduate degree course.

### 6.2.2 Stimuli

Forty high frequency (CobLog >.9) CCVC monosyllabic nouns were selected from the CELEX database (Baayen, Piepenbrock, & Gulikers, 1995) to be used as primes (see Appendix iii for full stimulus list). Words with double consonant onsets (e.g. plane, /plein/) which remained words after removing their initial phoneme (e.g. lane, /lein/) were selected. For each prime word a correct phoneme deletion target (match) and three incorrect targets (mismatch) words were listed. The incorrect targets were either a pseudo-word (PW, e.g. hain, /hein/); a phonologically plausible word (PP, e.g. rain, /rein/); or a phonologically implausible word (PI, e.g. cane, /kein/). Phonological plausibility related to the legality of the first phoneme of the incorrect targets as the second phoneme in the onset consonant cluster of the prime. While the /r/ in rain can plausibly follow the /p/ of plane, the /k/ in cane can not (i.e. /pkern/ is not phonologically plausible in English). Where available the lexical frequencies (CobLog, Baayen, Piepenbrock, & Gulikers, 1995) of the correct, phonologically plausible and phonologically implausible words were matched<sup>3</sup> (see Table 6.1). One-way analysis of variance showed no difference in the lexical frequency between the three word conditions (F[2,44] = .38, p > .1).

Stimuli were recorded by a female speaker and digitised at 16 bit, 44.1 kHz stereo as individual sound files. Statistical analysis of stimulus lengths showed no significant difference between the four target conditions (see Table 6.1; F[3, 117] = .71, p > .1).

Stimulus Type	Lexical Frequency (CobLog <sup>1</sup> )	Mean Duration (ms)	Example
Prime	-		[plern]
Correct	1.40 ± .64	615 ± 124	[lern]
Incorrect PW	-	610 ± 125	[hern]
Incorrect PP	1.55 ± .67	597 ± 108	[rein]
Incorrect PI	1.43 ± .69	604 ± 116	[kern]

<sup>1</sup> The CELEX Lexical Database (Baayen, Piepenbrock, & Gulikers, 1995)

Table 6.1 – Example words and pseudo-word for each condition with mean lexical frequency (CobLog<sup>1</sup>) and duration.

### 6.2.3 Design and Procedure

Auditory stimuli were presented to participants through inner auricular earphones (Etymotic<sup>TM</sup> research, Illinois, USA) at the start of a 2.5 s response

 $<sup>^{3}</sup>$  n = 23 out of 40

window, after which responses were deemed an error. Participants were instructed that they would hear pairs of words and needed to decide whether or not the second word they heard was the same as the first one, but with the first sound removed. Responses were made with keyboard keys positioned under the index finger of the participants' left and right hands.

At the beginning of the experiment participants were given an example trial of the phoneme deletion task that was not presented again thereafter. To ensure that all participants understood the instructions, a second example prime was given to which the participant was asked what they would expect the correct target to be. Participants were advised that it was the first sound that needed to be removed and not the first letter. Response side was counterbalanced across conditions and block order counterbalanced across participants. Each prime was presented in a random order once in the course of each block. Trials for each condition were evenly distributed across the blocks, such that 10 response trials were presented for each condition in each block.

During the EEG recording participants were asked to fixate on a red dot in front of them to minimise eye blinks and head movements.



Response Time (2447 ms)

Figure 6.2 – Trial Procedure. Note that the stimuli were presented with an ISI (inter-stimulus interval) of 1 s between the presentation of the prime and the target and an ITI (inter-trial interval) of 1 second after the response window before the presentation of the next trial. Although the target stimulus was shorter than the prime stimulus, trial duration was held

constant at the duration of the longest prime by adding silence to the end of each word/ pseudo-word.

### 6.2.4 EEG Recording and Processing

EEG recordings were made using a Neuroscan system (SynAmps, NeuroScan Inc., Texas, USA) from 32 electrode sites across the scalp (10/20 international system). The signal was digitised at 1 kHz, referenced to Cz and filtered online between 0.01 and 200 Hz before being digitally re-filtered off-line (zero phase shift low pass 35 Hz, slope = 48 dB/Oct). Bipolar recordings made from electrodes set above and below the left eye were used to mathematically correct blinks when the standard deviation of the blink model was below 0.005. Signals were then sliced into 1.1 s epochs, starting 100 ms before and ending 1000 ms after stimulus onset. Baseline correction was performed in reference to pre-stimulus activity. Individual averages were re-referenced to the global field power (GFP) produced across the scalp (average reference) before grand averages were calculated for each condition.

#### **6.2.5 Statistical Analysis**

Main ERP components were identified based on their typical topography, deflection and latency. Windows of analysis for each component were defined on the basis of the mean global field power (MGFP) across conditions and groups (Picton et al., 2000): 70 to 140 ms for the N1, 140 to 260 ms for the P2, 250 to 300 ms for the N2, 300 to 380 ms for the P3a, 240 to 360 ms for the P3b, and 450 to 700 ms for a Late Parietal Positivity (LPP). Peak detection was time-locked to the electrode of maximal amplitude for each component: Cz for the N1 and P2, Fz for the N2 and P3a,

and Pz for the P3 and LPP. In each case, mean amplitudes were measured at three contiguous electrodes chosen *a priori*, based on the known region of maximum sensitivity for each component (Picton et al., 2000): C3, Cz, C4 for the N1 and P2; FC1, Fz, FC2 for the N2 and P3a; and CP1, Pz, CP2 for the P3b and LPP.

Mean amplitudes were submitted to a 4 x 3 within- x 2 between- subject repeated measures ANOVA. Within-subject factors were: Condition (Match, PW, PP, PI) and electrode (three in all cases). The between-subject factor was group (control, dyslexic). A Greenhouse-Geisser correction was applied to electrode main effects and interactions where appropriate (Greenhouse & Geisser, 1959). Interactions involving the electrode factor were validated using vector normalisation (McCarthy & Wood, 1985). Unless otherwise specified, only significant main effects and interactions surviving normalisation (p < .05) are reported.

# 6.3 Results

### 6.3.1 Cognitive Assessment

Dyslexic participants' performance was poorer than controls on the reading and spelling subtests. However, no differences were observed for the non-verbal assessment measures and ADHD symptoms (Table 6.2; also see Appendix v, Table 2 for individual performance).

	Control		Dyslexic		
,	М	SD	М	SD	P-value
DAST Reading (words / min)	110	9	87	20	<.01
DAST Spelling (words / 2 min <sup>1</sup> )	34	4	29	4	< .01
DAST Non-verbal (range 0 - 8)	5	1	6	2	NS
WRAT Reading <sup>2</sup>	114	5	103	4	< .001
WRAT Spelling <sup>2</sup>	107	6	97	9	<.01
WAIS Matrix Reasoning (range 0 – 26)	19	3	20	4	NS
WAIS Digit Span (range 0 - 30)	18	5	17	3	NS
ADHD Symptom Scale					
Inattention (range 0 - 9)	2	2	3	3	NS
Hyperactivity (range 0 -9)	3	2	3	3	NS

<sup>1</sup> Based on the scoring criteria for this test, values are equal to the number of words spelt correctly in 2 minutes plus 8 additional points

<sup>2</sup> Standard Score

Table 6.2 - Cognitive Assessment. Means (M) and Standard deviations (SD) are shown for each score on the cognitive subtests. P-values are given for each significant effect based on a between-subjects ANOVA.

# 6.3.2 Behavioural Data

Both the dyslexic and control participants responded correctly to over 90 percent of trials on average across all conditions. However, dyslexic participants made more errors (mean =  $3 \pm 3$  errors) than the controls (mean =  $2 \pm 2$  errors, F[1,22] = 4.43, p < .05), see Figure 1. There was also a significant condition x group interaction (F[3,66] = 2.97, p < .05). Dyslexic adults did not differ across conditions,

but controls made significantly less errors in the phonologically plausible (PP) mismatch condition than both the match (M; t[11] = -2.49, p < .05) and pseudo-word (PW; t[11] = -2.31, p < .05) mismatch conditions.

A repeated measures ANOVA of reaction times for correct trials revealed that participants were faster to respond to matches than any of the mismatch trials (F[3,66] = 8.01, p <.001). A significant condition x group interaction was also found (F[3,66] = 3.66, p < .05): Control participants responded slower to the pseudo-word mismatches than the matches (t[11] = -2.25, p < .05), whereas the dyslexic participants responded significantly slower to all mismatch trials compared with match trials.



Figure 6.3 – Behavioural results. Bars depict reaction times in controls (left) and dyslexic adults (right) for the Match (grey bars) and Mismatch conditions (PW, PI, PP; white bars). Circles depict error rates. Error bars indicate standard errors in all cases.

### 6.3.3 ERP Results

Visual inspection of the grand average waveforms revealed a clear series of ERP peaks in all conditions and both groups: N1, P2 and N2 (Figure 6.4). The match condition also displayed parietal and frontal peaks in the P3 range. A late parietal positivity (LPP) was also observed for the mismatch conditions in both groups.

The N1 and P2 were both maximal at Cz, the N1 peaking at  $104 \pm 13$  ms and the P2 at 208  $\pm 24$  ms on average. No main effects or interactions of experimental factors were observed for the N1 or P2.

The N2 peaked at  $280 \pm 16$  ms and was maximal at Fz. There was a significant effect of condition on the amplitude of the N2 (F[3,66] = 19.57, p < .001). Multiple comparisons showed that this effect was the result of a greater N2 in response to the mismatches than matches (M – PW: t[23] = 5.30, p < .001; M – PI: t[23] = 5.99, p < .001;, M – PP: t[23] = 4.61, p < .001). No significant differences were found between any of the mismatches. No interactions were found for the N2 amplitude with the group factor.

The P3a peaked at 340 ms on average and was maximal at fronto-central sites. There was a significant effect of condition on the amplitude of the P3a (F[3,66] = 23.78, p < .001). Multiple comparisons showed that this effect was the result of a greater P3a in response to the matches than mismatches (C – PW: t[23] = 5.98, p < .001; C – PI: t[23] = 5.42, p < .001;, C – PP: t[23] = 6.84, p < .001). No differences were found between any of the mismatches: PW – PI (t[23] = 1.01, p > . 1), PW – PP (t[23] = 1.49, p > . 1), PI – PP (t[23] = 1.27, p > . 1). The condition effect was also found to interact with the group factor (F[3,66] = 5.92, p < .01; see Appendix vi, Fig.3 for individual performance). The P3a effect (match – mismatch) was significantly

smaller in dyslexic participants than controls (t[22] = 4.03, p < .001; mean difference =  $1.23 \mu$ V).

The P3b peaked at 288  $\pm$ 35 ms on average and was maximal at Pz. A significant effect of condition revealed that the P3b effect was present for the match trials only (F[3,66] = 31.07, p < .001). Importantly, no differences were identified between the mismatch conditions in the P3b range. The P3b effect did not interact with the group factor.

A late parietal positivity (LPP) that peaked at  $599 \pm 72$  ms on average over centro-parietal sites and was maximal at Pz was observed for mismatches (F[3,66] = 6.41, p < .01). Multiple comparisons showed this effect to be limited to the mismatches with no significant differences between the mismatch conditions: PW - PI (t[23] = 1.30, p > . 1), PW - PP (t[23] = 0.66, p > . 1), PI - PP (t[23] = -0.75, p > . 1).



Figure 6.4 – Grand average ERPs elicited by matches (correct; solid lines) and mismatches (incorrect PW, PI, PP; dashed lines) in controls (black lines) and dyslexic adults (grey lines). Shaded boxes depict the intervals of analysis for the P3a (FC1, Fz, FC2) and P3b (CP1, Pz, CP2).

# 6.3.4 ERP Component Amplitude Correlations with Cognitive Assessment Measures

A correlation analysis was performed on the mean amplitude of the P3a, P3b and N2 components. We failed to find any significant correlation of the P3a or P3b amplitude (match condition) at fronto-central sites (FC1, Fz, FC2) and Pz respectively, with the cognitive assessment measures (all > .1). The mean amplitudes of the N2 at Fz in response to the match or mismatch conditions did not correlate with the cognitive assessment measures either (all > .1).

# 6.4 Discussion

Performance on the cognitive assessment battery measures showed that dyslexic participants were significantly poorer at reading and spelling than controls. However, both groups performed equally well on tests of non-verbal reasoning and short-term memory span. In addition, there were no differences in the incidence of ADHD symptoms across groups. The overall pattern of scores was comparable with those reported in Chapter 5 for dyslexic adults with the same level of education.

Performance on the phoneme deletion task was high for both the dyslexic and control participants, although dyslexic participants made significantly more errors than controls. Compared to control individuals, dyslexic children and adults generally make a greater proportion of errors in articulating the target of a phoneme deletion than reported here (Bruck, 1992; de Gelder & Vroomen, 1991). However, the recognition task used here did not require production; therefore errors due to the confusion of phonological units at the stage of word production do not influence performance here. The absence of any differences in errors rates or reaction times between the PI and PP conditions showed that phonologically implausible mismatches were not easier to reject than phonologically plausible mismatches in either group. This suggests that phonotactic constraints were not helpful in distinguishing between matches and mismatches in either group. However, control participants were better at identifying phonologically implausible mismatches than pseudo-words and matches, whereas dyslexic participants performed equally in identifying the different mismatches.

Post-hoc analysis of the stimuli used revealed a characteristic of the phonologically implausible words that was not apprehended at first. Although many of the words selected as phonologically implausible (e.g. cane following plane) have an initial phoneme which cannot follow the initial phoneme of the prime in English (i.e., /k/ can not follow /p/), the co-articulated onset phonemes presented in some of the words could. This was often the case when primes began with a fricative /s/ (e.g., spin). /p/ is an aspirated voiceless stop in English. However, when preceded by /s/, /p/ is unaspirated. This subtle change in the acoustic signal results in the phoneme being perceived as voiced (i.e., spin without the /s/ sounds like bin and not pin; Ladefoged, 2001). Based on this, 35 percent of the PI words were in fact phonologically plausible. It must be kept in mind, however, both dyslexic and control participants correctly classified the matches and mismatches in over 90 percent of trials. Because the stimuli were not always phonologically consistent (e.g., the match for space was pace, which in fact is an orthographic match, and its PI mismatch was base, which effectively is a phonological match), we conclude that both control and dyslexic participants used an orthographic strategy to perform the task.

As a result of the interaction between expected acoustic and orthographic information any differences in the processing of the mismatches attributed to implausible or plausible phonological structure may be misleading. However, differences in the overall pattern of reaction times and error rates between the match and mismatch conditions that were observed in controls, but not in dyslexic participants, suggest sensitivity to differences in the mismatch conditions by controls that were not present for dyslexic participants.

No differences in the amplitude of the N1 or P2 were observed for condition or group. The lack of N1 amplitude differences between dyslexic and control participants reported here stands in contrast to the group interaction found for phoneme change detection (Chapter 5). The presence of these differences may be limited to a subset of dyslexic participants, explaining why this effect has been reported in some pure tone studies (e.g., Pinkerton, Watson, & McClelland, 1989) and not others (e.g., Yingling, Galin, Fein, Peltzman, & Davenport, 1986). However, the most likely explanation is that in the phoneme change detection experiment, participants were presented with two possible onset phonemes only (/p/ vs. /b/ in one block and /r/ vs. /g/ in the other), whereas in the present experiment, initial phonemes varied widely between stimuli. The perceptual variance of the initial phoneme in the present experiment is very likely to account for the absence of early perceptual effects on the ERPs.

As predicted the N2 amplitude was greater for mismatches than matches. The N2 did not show any interactions in the mismatches or with the group factor. The lack of differences in the N2 between mismatch conditions has been shown by other authors using similar phonological mismatches (Newman, Connolly, Service, & McIvor, 2003). Newman, Connolly, Service and McIvor (2003) presented control

adults with a phoneme deletion task similar to ours. In their study, three phoneme deletion mismatch conditions were also used. The first mismatch resulted from removal of the incorrect phoneme (e.g. clap became cap), the second mismatch resulted from removal of the whole consonant cluster (e.g. clap became ap) and the final mismatch was an irrelevant word (e.g. clap became nose). Newman *et al.* found no differences in the N2 peak amplitude between mismatches, concluding that the phonological mismatch effect of the N2 is an all-or-none process which is unaffected by the degree of similarity between the expected (primed) word and the one presented. The results of our study are consistent with Newman *et al.*'s conclusion. In sum, the absence of N2 modulations to changes in the mismatch conditions gives no clear indication as to the efficacy of implicit phonotactic processing in dyslexic adults relative to controls.

A P3a was shown for the matches with a similar topography and latency to that observed in Chapter 5. In contrast to Chapter 5 and consistent with Chapter 4, this P3a was significantly reduced for dyslexic participants as compared with controls. However, no correlations were shown with the amplitude of the P3a and reading or spelling performance. The lack of correlation may be due to a shift of baseline induced by the heterogeneity of the mismatch conditions. Since mismatch trials pertained to different phonotactic categories and since corresponding words started with systematically different phonemes, amplitude differences in the P3a range might have become less reliable, making correlations less likely.

A P3b was also was observed for the matches that peaked earlier than that reported in Chapter 5. Classically, oddball word stimuli elicit P300's in the 500-600 ms range (Bentin, 1987; Bentin, McCarthy, & Wood, 1985; Polich & Donchin, 1988). However, this delay in the P300 to word stimuli varies with the point at which the

standards and deviant words can be discriminated (Sussman et al., 2004). Since the oddball manipulation in this task occurred on the first phoneme, we would expect the P3b to be rather early. Using a similar phoneme deletion task Newman et al. (2003) reported a relatively early P3b peaking between 300 and 400 ms. The P3b did not however discriminate between dyslexic and control participants. Since the P3a is classically observed to task irrelevant changes it is not clear why differences were observed in the P3a rather than the P3b range. Unlike the classical oddball task, this study presented four conditions with equal frequency (25% each), of which one condition was a match and the others mismatches. This roving baseline creates a stimulus stream closer to that typical of the novelty oddball paradigm rather than the classical oddball, since the standard and deviant conditions are less clearly defined. Furthermore, the frontal P3a observed in a classical oddball has been shown to decrease with stimulus habituation, but increase with memory load (Wintink, Segalowitz, & Cudmore, 2001). Since the phoneme deletion task reported here is a task of high memory load, modulation of the P3a component is less surprising even for task relevant discriminations. In addition, the phoneme deletion stimuli for standards and deviants were continually changing for every trial, making the habituation of the P3a effect less likely.

Several major improvements could be made to this study. Importantly, statistical power is greatly reduced by the 4 condition design that was implemented. The use of a factorial design possibly examining the effect of non-word primes and targets versus real-word primes and targets would allow examination of sub-lexical processing more accurately. Even normally developing young children perform worse at identifying pseudo-words than real-words as phoneme deletion matches (M. Stuart, 1990). Furthermore, the use of non-word primes and targets would prevent the use of a purely orthographic strategy. Instead, phonological decoding would be required to ensure correct task performance.

## 6.5 Conclusion

Although not impaired for performance in detecting simple phoneme changes (Chapter 5), dyslexic participants are impaired for a more demanding phoneme awareness task (phoneme deletion). Furthermore, this impairment is indexed by a reduction in the P3a component. Dyslexic adults show differences in P3a amplitude for changes in task irrelevant phonological cues (Chapter 4) and in focused attention to highly demanding phoneme changes (phoneme deletion). These results are consistent with a specific deficit in attention to sub-lexical phonological cues.

# Chapter 7

# Focused Attentional Demands in an Awareness Task: Phonemes and Pure Tones

### 7.1 Introduction

The results of Chapters 1-3 suggest the presence of a phonological processing deficit in dyslexia that is significantly modulated by task demands. Although there is considerable evidence to support the presence of a specific phonological deficit in dyslexia, some evidence has suggested that a more general impairment in auditory processing could explain the deficits present in dyslexia (Wright, Bowen, & Zecker, 2000).

ERPs have been used to compare processing of pure tone sequences in dyslexic and control participants. A majority of these tasks involved simple detection of frequency changes in pure tones. Some studies have shown no difference between control and dyslexic participants in the amplitude of the P300 elicited by oddballs (e.g. Bernal et al., 2000; Rüsseler, Kowalczuk, Johannes, Wieringa, & Münte, 2002). However, Holcomb and colleagues (1986) using an oddball paradigm found a reduction in the P300 amplitude for dyslexic participants compared with controls. In contrast to the other studies, this study used a large inter-stimulus interval between each of the tones presented. Increasing the stimulus interval may have increased attentional and memory demands placed on the participants and may therefore be the cause of the reduced P300 amplitude.

In Chapter 5 we showed similar P300 amplitudes for dyslexic and control participants in a simple phoneme oddball task that is comparable to the P300s found in some simple tone frequency oddball studies (e.g. Bernal et al., 2000; Rüsseler,

Kowalczuk, Johannes, Wieringa, & Münte, 2002). However, in a more demanding phoneme awareness task (phoneme deletion, Chapter 6) we found a reduced P3a for dyslexic participants as compared with controls. Since phoneme awareness tasks and pure tone oddballs differ not only in the complexity of the auditory signal but also the attentional resources they require, a high demanding pure tone variant of the phoneme deletion task may show similar P3 reductions in dyslexic adults.

In this study we examined the specificity of impaired performance on phoneme awareness tasks in dyslexic adults by creating a non-linguistic (pure tone) equivalent of the phoneme deletion task. We hypothesized that if dyslexia is a consequence of a deficit in phoneme awareness, the P300 should be reduced only for phoneme deletions and not tone deletions.

# 7.2 Materials and Methods

### 7.2.1 Participants

Twelve developmental dyslexic adults registered with the Bangor Dyslexia Unit (mean age  $19 \pm 1$  year, 5 males, 1 left-handed) and 12 control adults (mean age  $21 \pm 3$  years, 3 males, 1 left-handed) all first language English speakers of the same level of education volunteered to participate. All dyslexic volunteers had a record of reading difficulties and were diagnosed dyslexic on the basis of a battery of standardized tests that focused on the discrepancy between verbal and nonverbal performance measures (Turner, 1997). The Barkley current symptom scale (Barkley & Murphy, 1998) was used as a self-report measure of Attention Deficit Hyperactivity Disorder (ADHD) symptoms, and an additional battery of subtests was used to assess reading, spelling, digit span and non-verbal reasoning (Table 7.1). Subtests were taken from the Dyslexia Adult Screening Test (DAST; Nicolson & Fawcett, 1997), WAIS-III (Wechsler, 1997) and Wide Range Achievement Test (WRAT-3; Wilkinson, 1993).

#### 7.2.2 Design & Stimuli

Two hundred words (primes) with the same consonant-vowel structure (CCVVC) were selected from the CELEX lexical database (Baayen, Piepenbrock, & Gulikers, 1995). Fifty of the selected words remained words after removal of their first phoneme (25% of the targets, e.g. plane – lane), and a 150 words (75% of the targets) by removing the initial phoneme of the primes and changing the initial phoneme of these words, made a new word (e.g. flame – game; see Appendix iv for a full stimulus list). The mean lexical frequency for both the match and mismatch words was  $1.3 \pm 0.6$  (CobLog)<sup>4</sup>.

Pure tone sequences that matched the individual phonemes present in the words were created using Matlab<sup>TM</sup> (The MathWorks Inc.). Individual tone durations were calculated from the average length of four examples of each phoneme randomly sampled from the word stimuli. Where possible, example phoneme durations were taken from the average duration of two onset and two final position phonemes. Overall, the word stimuli contained 31 different phonemes for each of which a pure tone was created with random frequency between 200 and 1260 Hz. Pure tones were separated in steps of 20 Hz to ensure perceivable differences between them. Once generated the tones were combined to form a match to the original words. To ensure a continuous auditory signal similar to that recorded for the words, the duration of each

<sup>&</sup>lt;sup>4</sup> Due to constraints on the availability of CCVVC words in the database, lexical frequencies were not available for all words. This constituted 12 percent of the matches selected and 13 percent of the mismatches selected.

tone was adapted so that it returned to baseline at the end, while maintaining as close to its original duration as possible.

During the experiment participants were required to perform the phoneme deletion task described in chapter 6. In a separate block participants were required to perform the same task with a tone sequence. After hearing 2 rapid tone sequences, separated by a gap of 1 second of silence, participants were required to press one key if the second tone sequence was the first deprived of its first tone and another key if it was not.

Initial pilot testing showed that adult control participants performed at around chance in this task (see pilot testing). The number of tones in the task was therefore reduced and the final tone in the sequence lengthened to cover the duration of the removed tone/s. Control participants only reached similar performance on both the tone and phoneme deletion tasks when the prime consisted of only two tones (see below).

### 7.2.3 Pilot Testing Stimuli

Three sets of six participants with no record of reading difficulties volunteered to participate in the pilot testing. Participants from all pilot studies were presented with the same phoneme deletion task, only the number of prime and target tones present in the tone deletion task changed.

By reducing the number of tones in the prime, task difficulty was matched between the phoneme and tone deletion tasks, according to task performance. Matched performance was observed when the prime was only 2 tones long (see Figure 7.1).



Figure 7.1 - Response rates across all 3 pilot experiments. n = 6 for each pilot; 4 males and 2 females (mean age 23± 1) participated in pilot 1; 6 females (mean age 23± 1) in pilot 2; and 1 male and 5 females (mean age 23± 2) in pilot 3. All pilot participants were right-handed. Error bars depict standard error in all cases.

### 7.2.4 Procedure

Participants were seated in a sound attenuated room and asked to make responses based on the pairs of words or tone sequences they heard. Reponses were made by pressing keyboard keys positioned under the participant's left and right index fingers. Participants were required to press one key if the second word or tone sequence they heard was the same as the first, but with the first phoneme or tone removed, and another key if it was not. Two blocks of the tone deletion task and two blocks of phoneme deletion task were presented to each participant. The order of blocks was counterbalanced across participants so that half of participants performed the tone task and half the phoneme task first. The side of response was counterbalanced within participants and between tasks, so that each participant made responses to the matches with their left and right finger in each task. Prime and target presentations were separated by a 1 second silence. Two trials were separated by a 1.2 second silence. Responses were accepted during a window of 2.5 seconds from the onset of the target stimulus, after which the trial was deemed an error.

# 7.2.5 EEG Recording and Processing

EEG was recorded from 32 Ag-AgCl electrodes placed over the scalp according to the extended 10-20 system and referenced to the vertex electrode (Cz, American, 1994). Recordings were sampled at 1 kHz and bandpass filtered on-line between 0.1 and 40 Hz, before being digitally refiltered offline (lowpass, 35 Hz, 48 dB/Oct). Impedances were kept below 9 k $\Omega$ . Eye blink artifacts were mathematically corrected when the standard deviation of the model was below 0.005 (Scan 4.2; Neuroscan Inc., Texas, USA). Any remaining artifacts were manually rejected upon visual inspection. Recordings were cut into 1100 ms epochs and baseline corrected according to the 100 ms pre-stimulus activity. Finally, individual ERPs calculated from the average of the trials in which the participants responded correctly were rereferenced to the global average reference and grand averages for each condition were computed.

### 7.2.6 Statistical Analysis

ERP amplitudes were analysed at three electrode sites based on the standard (*apriori*) component topographies: C3, Cz, C4 for the N1 and P2; FC1, Fz, FC2 for the N2 and P3a; and CP1, Pz, CP2 for the P3b and LPP. Search intervals for ERP peaks were identified on the basis of major modulations of the mean global field power (MGFP, Picton et al., 2000): 70 - 140 ms for the N1; 140 - 260 ms for the P2; 250 - 300 ms for the N2; 300 to 380 for the P3a; 240 - 360 ms for the P3b; and 450 - 700 ms for the LPP. The resulting mean amplitude and peak latency measures were subject to a repeated measures ANOVA: within subject factors were Task (phoneme or tone deletion); Oddity (Match, Mismatch); electrode (3 in all cases) and the between subjects factor was group (dyslexic, control). In addition, Pearson's correlations between the mean amplitude of the P3a and N2 at Fz and P3b at Pz and each of the behavioural assessment measures were computed.

# 7.3 Results

### 7.3.1 Cognitive Assessment

Dyslexic adults' showed poorer performance than controls on all verbal assessment measures (see Table 7.1; also see Appendix v, Table 3 for individual performance). On average, the control participants correctly read 39 words per minute and spelt 3.5 words per minute more than the dyslexic participants. Furthermore, the dyslexic participants wrote 4 words less than controls in the time allowed on average (dyslexics:  $30 \pm 2$  words; controls:  $26 \pm 2$  words), irrespective of errors (F[1,22] = 19.3, p < 0.001). A greater difference was found in the number of spelling errors, with

dyslexic participants making over twice as many spelling errors (mean =  $7 \pm 4$ ) than controls (mean =  $3 \pm 2$  spelling errors; F[1,22] = 9.07, p < 0.01).

Raw scores of reading and spelling (WRAT-3) showed that 10 of the 12 dyslexic participants (group mean =  $45 \pm 3$  raw WRAT score) were one standard deviation below that of the controls mean reading score ( $50 \pm 3$  raw WRAT score), and 9 (group mean =  $37 \pm 4$  raw WRAT score) fell one standard deviation below that of the controls mean spelling score ( $43 \pm 2$  raw WRAT score).

	Control		Dyslexic		
	М	SD	М	SD	P-value
DAST Reading (words / min)	112	11	73	15	<.001
DAST Spelling (words / 2 min <sup>1</sup> )	34	4	27	4	< .001
DAST Non-verbal (range 0 - 8)	6	2	6	2	NS
WRAT Reading <sup>2</sup>	108	6	98	8	< .01
WRAT Spelling <sup>2</sup>	105	5	90	11	<.001
WAIS Matrix Reasoning (range 0 – 26)	18	4	20	4	NS
WAIS Digit Span (range 0 - 30)	17	4	15	3	NS
ADHD Symptom Scale					
Inattention (range 0 - 9)	2	2	3	3	NS
Hyperactivity (range 0 -9)	3	2	4	2	NS

<sup>1</sup> Based on the scoring criteria for this test, values are equal to the number of words spelt

correctly in 2 minutes plus 8 additional points

<sup>2</sup> Standard Score

Table 7.1 - Cognitive Assessment. Means (M) and Standard deviations (SD) are shown for each score on the cognitive subtests. P-values are given for each significant effect based on a between-subjects ANOVA.

### 7.3.2 Behavioural Results

Dyslexic participants performed as well as controls on both the phoneme and tone deletion tasks (F[1,22] = 1.6, p >.1). The number of errors made for matches and mismatches differed significantly depending on which of the two tasks was being performed (F[1,22] = 28.64, p < .001). Both control and dyslexic participants made more errors on matches (oddballs) than mismatches in the phoneme deletion task (t[23] = 2.5, p < .05), but showed the inverse effect (more errors on mismatches than matches) for the tone deletion task (t[23] = -4.1, p < .001), see Figure 7.1.

Both groups of participants responded faster on average in the tone deletion than in the phoneme deletion task (F[1,22] = 6.56, P < 0.05).

Overall, dyslexic participants were slower than controls across all conditions (F[1,22] = 4.74, P < 0.05).



Figure 7.2 - Behavioural Results. Bars show reaction times and bullets error rates. Error bars depict standard deviations (SD) in all cases.

# 7.3.3 ERP Results

ERP components N1, P2, and N2 were observed in all conditions. In addition, a fronto-central P3a and centro-parietal P3b were found in the match conditions. A large parietally distributed positive component was also seen between 450 and 700 ms for the phoneme deletion mismatches (late parietal positivity, LPP). Grand average waveforms recorded at nine electrode sites for the phoneme deletion task are shown in figure 7.3 and the tone deletion task in figure 7.4 (also see Appendix vi, Fig.4 and 5 for individual performance in these tasks).



Figure 7.3 – Grand average ERPs for *phoneme deletion task* elicited by the match (solid line) and mismatch (dotted line) conditions in controls (black) and adult dyslexics (grey). Shaded boxes depict the interval of analysis of the P3b.


Figure 7.4 – Grand average ERPs for *tone deletion task* elicited by the match (solid line) and mismatch (dotted line) conditions in controls (black) and adult dyslexics (grey). Shaded boxes depict the interval of analysis of the P3b.

The amplitudes of the main ERP components (N1, P2, N2, P3a and P3b) all differed significantly between the phoneme and tone deletion task. Greater component amplitudes were recorded for the tone as compared with the word stimuli.

The N1 amplitude was significantly greater for the matches as compared with the mismatches (F[1,22] = 6.11, p < .05). A borderline interaction between task and oddity (F[1,22] = 2.47, p = .05) revealed an reduced N1 amplitude for tone matches (t[23] = 2.79, p < .05) compared with tone mismatches that was not present for phoneme matches (t[23] = -.34, p > .1; see Figure 7.5).



Figure 7.5 – Grand average ERPs elicited by matches (solid lines) and mismatches (doted lines) in the phoneme deletion (words; black) and tone deletion (grey) tasks.

A difference in the amplitude of the P2 was observed between dyslexic and controls participants dependent on the task being performed (F[1,22] = 4.63, p < .05),

see Figure 7.6. Post-hoc *t*-tests revealed no significant difference in the P2 amplitude between the phoneme and tone deletion tasks in the dyslexic participants (t[11] = 0.19, p > .1), but an increased amplitude for the tone deletion task in the controls (t[11] = 2.75, p < .05). Furthermore, the amplitude of the P2 was modulated in both groups by condition (match or mismatch) depending on the task (F[1,22] = 15.51, p < .01), see Figure 7.5. A difference was observable between the tone and word deletion tasks for the mismatch trials, such that a greater P2 was shown for the tone than word task (t[23] = 4.062, p < .001), but no difference was shown for the match trials (t[23] = -0.32, p > .1).



Figure 7.6 – Grand average ERPs elicited in the phoneme deletion task (solid lines) and the tone deletion task (doted lines) for controls (black) and dyslexic adults (grey).

A significant interaction between oddity and group was observed for the N2 (F[1,22] = 11.59, p < .01). Post-hoc *t* tests revealed a larger N2 for mismatches than matches in controls (t[11] = 2.54, p < .05), but the inverse effect in dyslexic participants (i.e. larger N2 for matches compared with mismatches; t[11] = -2.32, p < .05). A significant interaction was also observed for task x oddity (F[1,22] = 64.86, p < .001). This was the result of a difference in N2 amplitudes for all conditions except the phoneme and tone mismatch conditions which were not significantly different.

A fronto-centrally distributed P3a was observed for both groups and tasks (F[1,22] = 6.19, p < .05). A borderline interaction between oddity and group (F[1,22] = 3.95, p = .06], revealed a significant P3a effect (match – mismatch) in the controls (t[11] = 2.71, p < .05) that was absent in the dyslexic participants (t[11] = .45, p < .1). A significant interaction of task and oddity was also observed (F[1,22] = 17.95, p < .001). This interaction was determined by the presence of a significant P3a effect (match – mismatch) in the phoneme task (t[23] = 4.41, p < .001) that was absent in the tone task (t[23] = -1.26, p > .1). Figure 7.4 shows a similar P3a peak was present for both the match and mismatch conditions in the tone task, but not the phoneme task.

A parietally distributed P3b effect was observed for both tasks (F[1,22] = 61.65, p < 0.001). This modulation was significantly greater for the controls than the dyslexic participants (F[1, 22] = 10.48, p < 0.01), see Figures 7.3 and 7.4. Overall, the P3b amplitude was greater for tones than words in both groups (F[1,22] = 16.86, p < 0.001). However, the P3b modulation (deviant – standard) was greater in the phoneme deletion task (mean =  $2.49 \pm 1.74 \mu$ V) than the tone deletion task (mean =  $0.54 \pm 1.45 \mu$ V). This finding is reflected in the size of the effect at Pz (Cohen's d, J. Cohen, 1988), which was greater for the phoneme task (1.21) than the tone task (0.39).

Finally, a LPP showed a borderline effect of task and oddity (F[1,22] = 3.62, p = .07). This LPP was only observed for the mismatches in the phoneme deletion t[23] = -2.28, p < .05) and not the tone deletion (t[23] = -0.81, p > .1).

Direct discriminant function analysis was performed on the P3b amplitudes recorded at Pz for performance on each of the tasks. Discriminant function analysis examines the classification ability of a task by comparing group membership predicted by chance and group membership according to the categorically defined groups. Using this technique 8 dyslexic and 8 control participants (67%) were classified correctly from the P3b amplitude recorded at Pz in the tone deletion task. In an independent analysis, 9 dyslexic and 8 control participants (78%) were classified correctly on the basis of the P3b amplitude in the phoneme deletion task.

# 7.3.4 ERP Component Amplitude Correlations with Cognitive Assessment Measures

As in our previous phoneme deletion study (chapter 6) the timed and un-timed reading and spelling tests were examined for correlations with the N2, P3a and P3b ERP component amplitudes (see Appendix vii, Fig. 1 and 2 for correlation graphs). N2 amplitude for matches correlated with DAST spelling scores (r = +.33, n = 24, p < .05, one tailed) and DAST non-verbal reasoning scores (r = +.50, n = 24, p < .01, one tailed) but only in the phoneme deletion task.

The P3a amplitude recorded in both the phoneme (r = +.37, n = 24, p < .05, one tailed) and tone deletion (r = +.45, n = 24, p < .05, one tailed) correlated with DAST spelling scores. P3a amplitudes also correlated with WRAT reading (r = +.47,

n = 24, p < .05, one tailed) and spelling scores (r = +.35, n = 24, p < .05, one tailed), but only for the tone task.

The P3b amplitude measures in both tasks (phoneme and tone deletion) correlated with all verbal assessment measures including digit span, see Table 7.2.

P3b		DAST	DAST	DAST	WRAT	WRAT	WAIS	WAIS
		Read	Spell	NV	Read	Spell	NV	DS
Tone	r	.54	.55	-	.59	.68	<b>H</b> 0	.36
Match	Sig.	**	**	NS	**	***	NS	*
Phon	r	.41	.38	-	.62	.62	<b>1</b> 01	.55
Match	Sig.	*	*	NS	**	**	NS	**

\* p < .05 \*\* p < .01 \*\*\* p < .001 NS p > .1

Table 7.2 - Correlations of P3b mean amplitude and cognitive assessment measures (one tailed). Note that neither of the non-verbal measures correlated with P3b amplitude.

### 7.3.5 ERP Component Amplitude Correlations with Reaction Times

Participant reaction times and P3a, N2 and P3b mean amplitudes recorded in both groups were subject to a Pearson's correlation analysis. Significant correlations identified participants with faster reaction times as also showing larger component amplitudes. Reaction times most strongly correlated with the P3b amplitude, but also correlated with the P3a (see Table 7.3). The N2 amplitude did not correlate with reaction times in the either tasks.

#### a. Phoneme Deletion

RTs		N2 Match	P3a Match	P3b Match
Phon	r	-	34	51
Match	Sig.	NS	p = .05	**
b. Tone Del	etion			
RTs		N2 Match	P3a Match	P3b Match
Tone	r	2. <u>4</u>	46	40
Match	Sig.	NS	*	*

Table 7.3 – Correlations of (a) phoneme deletion and (b) tone deletion tasks with participant reaction times (one tailed).

### 7.4 Discussion

Dyslexic adults showed significantly poorer performance than controls on both the timed and un-timed tests of reading and spelling, although no differences were observed for tests of non-verbal reasoning, digit span or ADHD symptoms. Overall, these scores are comparable with those observed in Chapters 4-6 for dyslexic adults with a comparable level of education.

Similar rates of correct responses for dyslexic and control adults indicated that both groups were able to perform the deletion tasks successfully. This result stands in contrast to the findings reported in Chapter 6 where dyslexic participants were poorer at correctly classifying phoneme deletion targets as matches or mismatches. A limitation in the performance of the dyslexic participants is however represented by an increase in response times compared with controls. In chapter 6 we reported a lower number of correct responses but similar response times to controls in dyslexic participants. The reverse pattern reported here might be the result of a speed-accuracy trade-off affect, indicating a change in strategy from that seen in chapter 6. Consistent with this, other studies have reported the likely effects of speed-accuracy trade-offs in compensated dyslexic adults reading performance (Gillund & Ferraro, 1996), while others have attempted to distinguish sub-groups of dyslexic adults on the basis of speed (fluency) or accuracy deficits (Lovett, 1987). However, group discrimination on the basis of reading speed versus reading accuracy is more likely to relate to differences in individual compensation strategies than independent processing impairments. This is supported by cross-linguistic studies showing that in orthographically transparent languages dyslexic children have much greater deficits in reading speed than reading accuracy (Goswami, Ziegler, & Richardson, 2005; Landerl, Wimmer, & Frith, 1997).

Despite having matched the phoneme deletion and tone deletion tasks for difficulty as measured by similar errors rates in identifying the match trials in the pilot study, both control and dyslexic participants responded faster in the tone deletion task than in the phoneme deletion task. Since the rime of the prime words were maintained in the match and mismatch target words (e.g. fl*ame* – g*ame*), only identification of the first phoneme of the target word was necessary to perform the phoneme deletion task. Similarly for the tone deletion task, only one tone needed identification to correctly identify the tone deletion match. However, unlike the tones used here, phonemes do not have consistently sharp onsets, but evolve over time, varying not only in frequency but also rise time and intensity. The less sharp onsets of a majority of phonemes compared with tones are likely to result in the faster tone deletion than phoneme deletion performance shown here.

When errors were made in identifying the deletion matches there was a significant tendency for the members of both groups to classify word targets as

mismatches, but tone targets as matches. Although it is unclear why this would be the case, it does indicate that there is a clear difference in the way that tones and words were processed. Importantly, the word stimuli are open to top-down influences from lexical knowledge, whereas the tone stimuli are not. If this effect is the result of lexical influences, the use of pseudo-words in the phoneme deletion task should abolish this effect.

Comparing the ERP components recorded in response to the tone and phoneme deletion tasks revealed significantly greater component amplitudes for the tone stimuli than the word stimuli. These differences are probably the result of changes in the auditory signal between tasks. While phonemes differ in spectral changes over several frequency bands, pure tones are composed of changes in a single frequency band. In addition, the onset of the tones is consistently sharp and with a great deal of similarity between trials, whereas the same initial phonemes vary in their onset and acoustic signal between trials. This is likely to result is less individual trial variability in the EEG for the tone task than the phoneme task and therefore stronger component averages.

The N1 was reduced to matches compared with mismatches in both tasks. Reduction in the N1 response occurs with repeated stimulus presentations (Budd, Barry, Gordon, Rennie, & Michie, 1998; Näätänen & Picton, 1987). In our tasks stimuli presented in the prime were repeated in the target in match trials, but not mismatch trials. This is supported by greater N1 differences between matches and mismatches for the tone deletion compared with the phoneme deletion. Since the exact acoustic signal from the prime is repeated in the target tones, while allophonic (within phoneme category) variations will exist between the prime and target phonemes.

Differences in the P2 amplitude between the phoneme deletion and tone deletion tasks were only present for controls. This may reflect differences in shortterm memory representations that are not present for dyslexic participants. Importantly, in both dyslexic and control participants' differences in the P2 amplitude between the phoneme and tone deletion tasks were restricted to the mismatches. This supports the suggestion of differences in short-term memory representation between trials since more trials are present in the averages for mismatches than matches.

In control participants the N2 amplitude was greater for mismatches than matches in both tasks. This is consistent with N2 amplitude differences observed in response to implicit phonological expectancy in other studies (e.g., Connolly, Phillips, Stewart, & Brake, 1992; van den Brink, Brown, & Hagoort, 2001). These studies show greater N2 amplitudes for unexpected phonological changes compared with expected ones in sentence contexts. Furthermore, Newman et al. (2003) found a comparable N2 amplitude increase for unexpected words (mismatches) compared with expected words (matches) in a phoneme deletion context similar to ours. Importantly, dyslexic participants in our study showed the inverse effect to controls; a greater N2 was recorded to match trials compared with mismatch trials. Since the size of the effect was comparable between dyslexic and control participants, these results suggest that dyslexic participants' implicit phonological processing abilities were impaired. Interestingly, N2 amplitude correlated with spelling scores and non-verbal reasoning, but not performance on the phoneme or tone deletion task itself. This is consistent with the N2 modulation as an index of implicit phoneme processing and not explicit phoneme awareness.

Consistent with findings reported in Chapter 6, a P3a modulation was observed for oddity in the phoneme deletion task. However, despite a clear P3a peak,

P3a amplitude was not modulated by oddity in the tone deletion task (i.e. similar P3a amplitudes were found for match and mismatch conditions. Furthermore, the P3a modulation observed in control participants was not present in dyslexic participants. Using a similar phoneme deletion task (Chapter 6) we failed to find any correlations of P3a amplitude and independent verbal or non-verbal performance measures. In this study we found P3a amplitude to correlate with DAST spelling scores only. Therefore, shifts in attention characterised by the P3a only weekly discriminate dyslexic participants on demanding focused attention tasks.

A large P3b was observed for both dyslexic and control participants in both tasks. However, the P3b modulation was greater in the phoneme deletion task than the tone deletion task. This may reflect a difference in discriminability between the tone deletion and phoneme deletion tasks, since P3b amplitudes are known to be reduced for stimuli that are harder to discriminate. However, faster reaction times to the tone deletion task compared with the phoneme deletion task suggest that the tone deletion targets were not harder to discriminate than the tone deletion targets.

The P3b amplitude was significantly reduced for dyslexic participants compared with controls across both tasks. Inconsistent with a pure phonological deficit the reduction of P3b for both tasks suggests an impairment that spans nonlinguistic and linguistic auditory stimuli. Furthermore, the P3b amplitude correlated with reading and spelling performance similarly for the tone deletion and phoneme deletion task. Discriminant analysis showed that P3b amplitude in the tone deletion task categorised 67 % of the participants correctly as dyslexic or control, with one additional dyslexic participant being categorised correctly from the P3b amplitude in the phoneme deletion task. Finally, the P3b amplitude correlated positively with reaction times on the phoneme deletion and tone deletion tasks which discriminated

the dyslexic and control participants. Overall the P3b modulations observed here suggest an attentional resource limitation in dyslexic adults that may be causal to phoneme awareness deficits and reading and spelling deficits.

A final component, the LPP, although it did not discriminate the groups was of some interest due to its presence only for the word stimuli. This component was also observed in the previous phoneme deletion experiment (Chapter 6) and is likely to relate to a process of re-evaluation that is specific to the top-down lexical processes available for word stimuli.

#### 7.5 Conclusion

This study examined the specificity of the P3a/P3b reductions we found for demanding phoneme awareness, but not simple phoneme detection tasks. Previously, large differences in the attentional and memory demands of simple auditory and complex phoneme awareness tasks have made it difficult to separate the influence of general attention and attention to phonology in the manifestation of dyslexia.

The reduced P3b to both the tone and phoneme deletion tasks reported here show that dyslexia is not a disorder limited to the processing of phonemes. The equal discriminative function of the P3b amplitude recorded in the tone and phoneme tasks further supports this conclusion. In light of the findings reported in Chapters 4 - 6, dyslexia may be better described as a deficit of attention in tasks of high processing load. It remains to be seen whether this deficit is specific to the auditory modality or also effects the visual processing of dyslexic adults.

# **Chapter 8**

# Attention Capacity for Discriminating Simple Visual and Auditory Stimuli

#### 8.1 Introduction

Perception is under the control of a limited attention system. Whether attention modulates environmental input early in the perception process (e.g. Broadbent, 1958) or late (e.g. Norman, 1968), attentional processes influence our conscious awareness of the perceivable world. Some tasks place more pressure on the attention system than others, either temporally or in terms of capacity. For instance, tasks requiring rapid shifts of attention and inhibition of distracters are more demanding than simple detection tasks. Reading is an example of a highly demanding task in terms of attentional resources. Even at the single word level reading requires the processing of multiple sources of information, phonological, orthographic and semantic. Furthermore, in the context of natural reading, words are not presented in isolation but amongst neighbours which need to be analysed independently. Words surrounding the word at fixation may act as distracters which are difficult to inhibit at any time.

In Chapter 7 we presented evidence that high-functioning dyslexic adults show deficient allocation of attention in the processing of pure tones as well as phonemes in deletion tasks. The suggestion of an attentional deficit in developmental dyslexia is not new (e.g., Facoetti, Lorusso, Paganoni, Umilta, & Mascetti, 2003; Facoetti, Paganoni, & Lorusso, 2000; Facoetti, Paganoni, Turatto, Marzola, & Mascetti, 2000) but there is little or no consensus on the type of attentional limitation that might be involved. Some studies have hinted a deficit in spatial shifts of attention {Buchholz et

al., 2005; Facoetti & Turatto, 2000; Facoetti, Turatto, Lorusso, & Mascetti, 2001; Hari & Renvall, 2001; Hari, Renvall, & Tanskanen, 2001; Nicolson & Fawcett, 1990; Roach & Hogben, 2004), others have suggested a deficit in non-spatial but rapid shifts of attention (Hari & Renvall, 2001; Hari, Valta, & Uutela, 1999; Renvall & Hari, 2002; Visser, Boden, & Giaschi, 2004), yet other authors have proposed that dyslexia is better characterised as a deficit in attention capacity or automatisation rather than in its ability to shift from one object to another (Moores, Nicolson, & Fawcett, 2003). Spatial attention deficits are likely to affect accurate reading performance by disrupting the positions of letters in words (Cornelissen, Richardson, Mason, Fowler, & Stein, 1995), whereas attentional capacity deficits are more likely to affect reading by reducing accuracy and fluency.

In chapter 6 and 7, we have found that dyslexic adults show signs of limited attention resources to demanding auditory tasks, whether phonological (Chapter 6) or phonological and nonverbal (Chapter 7), that cannot easily be characterised as requiring shifts in attention. Here we decided to test the attentional capacity of dyslexic adults more directly and nonverbally by manipulating processing load in both the auditory and the visual modalities using a nonverbal oddball paradigm. Many studies have examined visual and auditory aspects of attention processing in dyslexic participants, but few have examined visual and auditory processing in the same samples of dyslexic and control participants.



Figure 8.1 – Comparison of some stimulus features in the visual and auditory modalities. We chose to manipulate shape and luminance in the visual modality and pitch and volume in the auditory modality.

To manipulate perceptual load in an oddball paradigm, we measured performance on two stimulus features either independently or together in each modality (visual, auditory): Intensity (luminance /volume) and form (shape / pitch), see Figure 8.1. In other words, participants were asked to spot a specified target of low frequency, which differed from the distracters according to one feature (e.g., luminance *or* shape in the visual modality) or the two features simultaneously (e.g., luminance *and* shape in the visual modality).

Studies assessing magnocellular function in dyslexic individuals have used rapid transient visual stimuli (see Chapter 2). To avoid confounding effects of potential magnocellular deficits, we used a slow stimulus presentation rate (ISI = 1600 ms). Although colour changes are associated more with parvocellular function and luminance with magnocellular function, we decided to manipulate luminance rather than colour because of potential verbal strategies in dealing with colour variations. In any case, by using highly contrasted stimuli, we insured that the visual stimuli would require a significant parvocellular contribution (Ellemberg, Hammarrenger, Lepore, Roy, & Guillemot, 2001).

The aims of this study were (a) to examine potential deficits in attention resource allocation independent of language processing in dyslexic adults and (b) to test the generalisation of this deficit across two sensory modalities.

We hypothesized that an amodal attention deficit in developmental dyslexia would result in a significant reduction of the P3b elicited by deviant stimuli in a dual feature discrimination task relative to a single feature discrimination task. On the basis of Chapter 1 and 2, we also hypothesized that dyslexic and control participants would not differ in each of the single feature detection tasks.

#### 8.2 Materials and Methods

#### 8.2.1 Participants

Twelve developmental dyslexic adults and 12 control adults took part in the experiment. One dyslexic adult was removed from the analysis due to excessive movement artefacts and one control adult was removed as an outlier (false alarms were more than 2 standard deviations above all other participants). The remaining 11 developmental dyslexic adults (mean age  $20 \pm 2$  years, 2 males) and 11 control adults (mean age  $20 \pm 1$  year, 3 males) were right-handed native English speakers with normal or corrected-to-normal visual acuity and no known hearing impairments. Dyslexic volunteers were referred by the Bangor Dyslexia Unit. All had a record of reading difficulties and were diagnosed dyslexic on the basis of a battery of standardised tests that focused on the discrepancy between verbal and nonverbal performance (Turner, 1997). Participants matched for level of education were

administered an additional dedicated battery of subtests to assess differences in reading and spelling. Subtests were taken from the Dyslexia Adult Screening Test (DAST, Nicolson & Fawcett, 1997), WAIS-III (Wechsler, 1997) and Wide Range Achievement Test (WRAT-3, Wilkinson, 1993). In addition, the Barkley current symptom scale (Barkley & Murphy, 1998) was used as a self-report measure of Attention Deficit Hyperactivity Disorder (ADHD) symptoms to control for potential co-morbidity effects.

#### 8.2.2 Stimuli

The visual stimuli were two abstract shapes covering an equal surface and presented at the centre of a  $300 \text{ cdm}^2$  TFT monitor within 1 degree of visual angle (see Figure 8.2)., The two variants of each display were created by changing the luminance of the shape by 50%, making one variant brighter and the other darker than the background while the contrast between the two variants remained constant.

The auditory stimuli were two pure tones (Frequency = 1000 and 2000 Hz) of equal duration (200 ms) digitized at 44.1 KHz and presented to participants through inner auricular earphones (Etymotic<sup>TM</sup> Research, Illinois, USA). The two variants of each tone were created by modulating signal amplitude by 50%.



Figure 8.2 – Visual displays. Target shape (T; top left) with lower luminance distracter (top right), distracter shape (bottom left) and lower luminance distracter shape (bottom left).

#### 8.2.3 Design and Procedure

An oddball paradigm involving 150 (75 %) distractor trials and 50 (25 %) target trials in all cases was implemented. Participants were asked to press a keyboard button with their right index finger on each occurrence of the target, which was always the same physical stimulus in all conditions (i.e., whether they had to attend to one or two features) in any one modality. Participants were presented with the target stimulus prior to the first block in each modality. In the visual version of the experiment, participants were asked to discriminate targets from distracters on the basis of shape, luminance or both features (See Figure 8.3). In the auditory version, participants were required to discriminate target tone from distracter tones on the basis of frequency, amplitude or both features. Trials were pseudo-randomised such

that targets were always separated by at least two distracters. Stimuli were presented for 200 ms, after which an interval of 1.6 seconds elapsed before the start of the next trial. A 1.5 second interval after stimulus onset was allowed for responses, beyond this a trial was deemed an error.

In the auditory task participants were asked to fixate on a red dot in front of them to minimise eye blinks and head movements. The order of testing modality (auditory and visual) was counterbalanced across participants. Single feature discrimination tasks were presented first to ensure that each participant received the same amount of training in these tasks before performing the conjunction task.





#### 8.2.4 EEG Recording and Processing

EEG recordings were digitized at 1 kHz from 64 Ag/AgCl electrodes conforming to the extended international 10-20 convention and referenced to Cz. Bipolar recordings were made from electrodes set above and below the left eye. Continuous recordings were band pass filtered on-line between 0.01 and 200 Hz before being digitally re-filtered off-line (zero phase shift low pass 35 Hz, slope = 48 dB/Oct). Eye blinks were mathematically corrected when the standard deviation of the blink model was below 0.005 (Scan 4.2; Neuroscan Inc., Texas, USA). Signals were then sliced into 1.1 s epochs, starting 100 ms before and ending 1000 ms after stimulus onset. Baseline correction was performed in reference to pre-stimulus activity. Individual averages were re-referenced to the global field power (GFP) produced across the scalp (average reference) before grand averages were calculated for each condition.

#### 8.2.5 Statistical Analysis

Main ERP components were identified based on their typical topography, deflection and latency. Windows of analysis for each component were defined on the basis of the average peak latencies within each modality (Picton et al., 2000). Intervals were calculated as  $\pm 30$  ms of the average peak latency, see Table 8.1.

	Intervals (ms)				
Component	Visual	Auditory			
P1	70 - 160	100 201			
N1	140 - 200	60 - 120			
P2	190 - 250	130 - 190			
P3b	330 - 390	250 - 310			

Table 8.1 - Component intervals for auditory and visual modalities.

Peak detection was time-locked to the electrode of maximal amplitude for each component: P08 for the P1 and N1, FCz for the P2 and Pz for the P3b in the visual presentation; Cz for the N1 and P2, and Pz for the P3b in the auditory presentation. In each case, mean amplitudes were measured at three electrodes selected *a priori* for each modality, based on the known region of maximum sensitivity for each component (Picton et al., 2000): O1, Oz, O2 for the P1 and N1; C1, Cz, C2 for the P2 and CP1, Pz, CP2 for the P3b for the visual presentation; and C1, Cz, C2 for the N1 and P2; and CP1, Pz, CP2 for the P3b in the auditory presentation.

Widespread latency, amplitude and topographic differences have previously been observed for the P3b between modalities suggesting independent generators of the P3b in auditory and visual oddball paradigms (e.g. Johnson, 1989). Therefore, only qualitative comparisons between the two modalities are advisable. Furthermore, since we made independent hypotheses for each task, 3 separate analyses were performed for each modality. Changes in the variability of responses were expected for the conjunction discrimination tasks as compared with the single feature discrimination tasks, making it necessary to perform independent analyses.

### 8.3 Results

#### 8.3.1 Cognitive Assessment

Dyslexic and control participants did not differ in their measures of nonverbal performance or ADHD hyperactivity symptoms (Table 8.2; also see Appendix v, Table 4 for individual performance). However, dyslexic adults performed significantly more poorly than controls in the two reading subtests and in the two spelling subtests used. Furthermore, dyslexic participants were poorer at the digit span test than controls and rated themselves significantly higher on measures of inattention than controls.

	Cor	Control		exic	
	М	SD	м	SD	P-value
DAST Reading (words / min)	112	27	86	21	<.05
DAST Spelling (words / 2 min <sup>1</sup> )	34	4	28	3	< .01
DAST Non-verbal (range 0 - 8)	5	2	5	1	NS >.1
WRAT Reading <sup>2</sup>	113	5	105	8	< .01
WRAT Spelling <sup>2</sup>	110	5	93	7	<.001
WAIS Matrix Reasoning (range 0 – 26)	20	4	19	2	NS >.1
WAIS Digit Span (range 0 - 30)	18	5	14	3	<.05
ADHD Symptom Scale					
Inattention (range 0 - 9)	2	2	4	3	<.05
Hyperactivity (range 0 -9)	2	2	2	2	NS >.1

<sup>1</sup>Based on the scoring criteria for this test, values are equal to the number of words spelt

correctly in 2 minutes plus 8 additional points

<sup>2</sup> Standard Score

Table 8.2 - Cognitive Assessment. Means (M) and standard deviations (SD) are shown for each score on the cognitive subtests. P-values are given for each significant effect based on a between subjects ANOVA.

#### 8.3.2 Behavioural Results

Independent one-way ANOVAs were performed for each task and modality.

Dyslexic participants were significantly slower at responding in the shape discrimination task (F[1,20] = 10.80, p < .01), luminance discrimination task (F[1,20] = 5.02, p < .05) and shape and luminance conjunction task (F[1,20] = 6.00, p < .05) than controls. No significant differences were observed in reaction times for dyslexic and control participants in any of the auditory discrimination tasks.



Figure 8.4 – Behavioural results. Reaction times in controls (white) and dyslexic adults (grey) for the (a) form discrimination, (b) intensity discrimination and (c) form and intensity discrimination. Error bars indicate standard errors in all cases.

Hit rates were too high to reveal any statistical differences. Average

percentages of correct responses are displayed in Table 8.3.

Modality		Visual		Auditory			
Discrimination	Shape	Luminance	Shape & Luminance	Pitch	Volume	Pitch & Volume	
Controls	99 (1)	99 (2)	97 (3)	97 (4)	99 (1)	99 (2)	
Dyslexics	100 (1)	99 (2)	98 (3)	97 (3)	98 (2)	98 (2)	

Table 8.3 – Mean percentage response rates for each task. Standard deviations are shown in parentheses.

The percentage of participants scoring 100 % correct is shown in Table 8.4. Overall, ceiling performance was reached by 55 % of controls and 70% of dyslexic participants in the visual task. In the auditory task, 64 % of participants reached ceiling and 30 % of dyslexic participants.

Modality		Visual		Auditory			
Discrimination	Shape	Luminance	Shape & Luminance	Pitch	Volume	Pitch & Volume	
Controls	64	73	27	55	73	64	
Dyslexics	91	64	55	18	36	36	

Table 8.4 – Percentage of participants reaching ceiling (100 % correct) for each task.

The number of false alarms made by participants was too small to show any significant differences between tasks or groups (Table 8.5; also see Appendix vi, Fig. 6 and 7 for individual performance).

Modality		Visual		Auditory			
Discrimination	Shape	Luminance	Shape & Luminance	Pitch	Volume	Pitch & Volume	
Controls	0 (1)	0 (0)	2 (2)	3 (3)	0 (1)	1 (1)	
Dyslexics	0 (0)	0 (1)	2 (2)	3 (3)	1 (1)	2 (2)	

#### 8.3.3 ERP results

Three clear ERP components were observed in both groups for the auditory presentation: N1, P2, and P3b. An occipital P1 an N1 were observed for the visual presentation along with a P2 and P3b similar to those observed in the auditory task.

### 8.3.3.1 Visual Presentation

The P1 and N1 were both maximal at P08 and peaked at  $131 \pm 19$  ms and 180  $\pm 17$  ms on average, respectively. A P2 was maximal at FCz and peaked at  $217 \pm 17$  ms on average. A P3b was visible over centro-parietal sites and maximal at Pz. The P3b peaked at  $360 \pm 19$  ms on average.

#### 8.3.3.1a Form (shape) discrimination

No significant main effects or interactions were observed for the P1 or N1 in the shape discrimination task.

A main effect of oddity was observed for the amplitude of the P2 (F[1,20] = 9.55, p < .01; Figure 8.5). The P2 amplitude was greater for the infrequent (deviant) shape than the frequent (standard) shape (t[21] = 9.17, p < .001).

The P3b amplitude was significantly modulated by shape oddity (F[1,20] = 130.7, p < .001) and this effect interacted with group (F[1,20] = 4.46, p < .05). Greater P3b amplitude was observed for the control participants as compared with the dyslexic participants.



Figure 8.5 – Grand average ERPs for shape discrimination task elicited by deviants (solid line) and standards (dotted line) in controls (black) and dyslexic adults (grey).

#### 8.3.3.1b Intensity (luminance) discrimination

No significant main effects or interactions were observed for the P1.

A significant effect of oddity was observed for the N1 (F[1,20] = 33.64, p < .001) and P2 amplitudes (F[1,20] = 29.06, p < .001), see Figure 8.6. A greater N1 and P2 amplitude were observed to the higher luminance shape than the lower luminance shape (t[21] = -5.83, p < .001; t[21] = 9.90, p < .001, respectively).

The P3b amplitude was significantly modulated by luminance oddity (F[1,20] = 151.87, p < .001), but this effect did not interact with group.



Figure 8.6 – Grand average ERPs for luminance discrimination task elicited by deviants (solid line) and standards (dotted line) in controls (black) and dyslexic adults (grey).

## 8.3.3.1c Form and intensity (shape and luminance) discrimination

No significant main effects or interactions were observed for the P1.

The N1 amplitude was significantly modulated by conjunction deviants (F[1,20] = 5.00, p < .05). A greater N1 amplitude found for the higher luminance deviant shapes than the lower luminance standard shapes (t[21] = -2.29, p < .05), see Figure 8.7.

No significant main effects or interactions were observed for the P2 amplitudes.

The P3b amplitude was modulated by the conjunction deviants (specific shape and high luminance; F[1,20] = 64.21, p < .001). This effect did not interact with the group factor.



Figure 8.7 – Grand average ERPs for shape and luminance conjunction discrimination task elicited by deviants (solid line) and standards (dotted line) in controls (black) and dyslexic adults (grey).

#### 8.3.3.2 Auditory Presentation

The N1 and P2 were maximal at Cz and peaked at 99  $\pm$ 9 ms and 172  $\pm$  15 ms on average, respectively. The P3b was maximal over centro-parietal regions and peaked at 278  $\pm$  22 ms on average.

### 8.3.3.2a Form (pitch) discrimination

The N1 amplitude showed a borderline effect of group (F[1,20] = 3.60, p =

.07). N1 amplitude was greater for dyslexic participants than controls.

No significant main effects or interactions were observed for the amplitude of the P2.

The P3b amplitude was significantly modulated by pitch oddity (F[1,20] = 67.26, p < .001) and this effect interacted with group (F[1,20] = 4.43, p < .05). A greater P3b was observed for the control participants compared with the dyslexic participants, see Figure 8.8.



Figure 8.8 – Grand average ERPs for pitch discrimination task elicited by deviants (solid line) and standards (dotted line) in controls (black) and dyslexic adults (grey).

#### 8.3.3.2b Intensity (volume) discrimination

No significant main effects or interactions were observed for the amplitude of the N1 to intensity changes.

A significant effect of intensity was observed for the P2 amplitude (F[1,20] = 26.15, p < .001). The P2 amplitude was greater to the higher volume (deviant) tones than the lower volume (standard) tones (t[21] = 4.89, p < .001), see Figure 8.9.

The P3b amplitude was significantly modulated by volume oddity (F[1,20] = 144.46, p < .001). A significant oddity x group interaction was also observed for the P3b amplitude (F[1,20] = 11.58, p < .01). A greater P3b was observed for the control participants compared with the dyslexic participants.





#### 8.3.3.2c Form and intensity (pitch and volume) discrimination

N1 amplitude showed a borderline effect of group (F[1,20] = 4.27, p = .05). N1 amplitude was greater for dyslexic participants than controls.

The P2 and P3b were both modulated by conjunction deviants (F[1,20] = 13.63, p < .01 and F[1,20] = 76.51, p < .001, respectively), see Figure 8.10. These effects did not interact with the group factor.



Figure 8.10 – Grand average ERPs for pitch and volume conjunction discrimination task elicited by deviants (solid line) and standards (dotted line) in controls (black) and dyslexic adults (grey).

# 8.3.4 P3b Component Amplitude Correlations with Cognitive Assessment Measures

Pearson's correlations were performed for P3b amplitude and the cognitive assessment measures (see Appendix vii, Fig. 3, 4 and 5 for correlation graphs).

A single significant positive correlation between the P3b amplitude observed to shape discrimination and DAST spelling was observed in the visual task (r = .41, p < .05). No correlations were observed with any of the cognitive assessment measures for the visual intensity and combined form and intensity oddball tasks.

The auditory P3b amplitude for both pitch and intensity correlated with a range of cognitive assessment measures.

Auditory		DAST	DAST	DAST	WRAT	WRAT	WAIS	WAIS
P3b		Read	Spell	NV	Read	Spell	NV	DS
pitch	r	.16	.38	.43	.43	.54	.28	.56
Distracter	Sig.	NS	*	*	*	**	NS	**
volume	r	.40	.42	.09	.39	.53	.21	.60
Distracter	Sig.	*	*	NS	*	**	NS	**
pitch & volume	r	.31	.23	19	.28	.34	07	.34
Distracter	Sig.	NS	NS	NS	NS	.06	NS	.06

\* p < .05 \*\* p < .01 NS p > .1

Table 8.5 – Correlation matrix of P3b mean amplitude and cognitive assessment measures in the auditory tasks (one-tailed).

## 8.4 Discussion

The cognitive assessment performance of dyslexic adults showed a similar pattern to that reported in previous chapters. However in this study, dyslexic adults also had poorer digit span scores than controls. Although this difference was not observed in our previous studies employing similar dyslexic adult samples, poorer digit span performance is usually found for large groups of dyslexic participants compared with controls (e.g. Hatcher, Snowling, & Griffiths, 2002). Furthermore, in this study the dyslexic participants' measure of inattention was significantly higher than that of controls. Although this score was not sufficiently discrepant to warrant screening of attention disorder (Barkley & Murphy, 1998), it is possible that poorer inattention in this dyslexic sample on average related to poorer digit span performance. Consistent with this view, children diagnosed with ADHD have poorer digit span scores than controls (Loge, Staton, & Beatty, 1990). Even more importantly, subtypes of ADHD adolescences with predominately inattentive traits show poorer digit span performance than predominately hyperactive subtypes (Schmitz et al., 2002). Overall the impaired digit span and elevated inattention scores in the dyslexic participants are likely to influence behavioural performance and ERP modulations in the oddball task. Working memory representations are important for change detection (e.g., Berti & Schroger, 2003; Tomporowski & Tinsley, 1994), this is especially true for oddball tasks with long inter-stimulus intervals like this one (Schroger, 1996; Schroger & Winkler, 1995).

Visual task performance revealed that dyslexic participants were slower to respond to the shape discrimination, luminance discrimination and the shape and luminance conjunction than controls. Reduced sensitivity to luminance contrasts has been observed in dyslexic participants previously (cf. Chapter 2), however investigation of these sensitivity differences have predominately been restricted to threshold discriminations rather than changes in speed of identification (Bednarek & Grabowska, 2002; Cornelissen, Richardson, Mason, Fowler, & Stein, 1995; Demb, Boynton, Best, & Heeger, 1998). These impairments in luminance thresholds have mainly been interpreted as evidence for a magnocellular deficit in developmental dyslexia (Greatrex & Drasdo, 1995). However, Stuart, McAnally and Castles (2001) using a computer simulation showed that at least some of the reported increases in luminance thresholds in developmental dyslexic could be explained by a deficit in attention. Since self-report scores of inattention were greater for the dyslexic participants than the controls in our study, we can not rule out inattention as a possible cause for the slower reaction times in visual performance.

Slower performance of dyslexic participants in the shape discrimination task is surprising, however. One possible explanation for this effect is that controls may be more prone to using verbal labels to aid stimulus discrimination, whereas dyslexic participants may be less prone to verbal labelling. However, the use of abstract shapes made verbal labelling rather unlikely. Furthermore, Gerber and White (1983) found no differences in the visual recognition memory performance of dyslexic children for stimuli which could be easily labelled (e.g. letters and geometric shapes) and stimuli which could not (abstract shapes). This suggests that impairment in the recognition of shapes from memory in dyslexic participants is not merely the consequence of poor verbal labelling skills.

It is important to note that the shapes presented in this study encompassed the same area and were therefore only different in their spatial configuration. While categorisation of simple geometric shapes (Sperling, Lu, & Manis, 2004) and the recognition of complex figures (e.g. faces, Rüsseler, Johannes, & Münte, 2003) are not impaired for dyslexic adults, some studies have reported the presence of a left spatial neglect in a proportion of dyslexic individuals (Eden, Wood, & Stein, 2003; Hari, Renvall, & Tanskanen, 2001). Although not designed for this purpose the shapes used in our task were discriminable in the upper, lower, left and right visual fields independently. The disparity in recognition performance in some tasks and evidence of spatial neglect in others may result from deficits in visual discrimination that are limited to feature discrimination rather than global shape configuration (von Karolyi, 2001; von Karolyi, Winner, Gray, & Sherman, 2003).

In both the visual and auditory tasks systematic N1 and P2 differences were found suggestive of changes in visual and auditory perceptual features as well as
changes in memory representation for the stimuli (Conley, Michalewski, & Starr, 1999).

In contrast to our prediction, the P3b amplitude in both the visual and auditory conjunction tasks were similar in amplitude for controls and dyslexic participants, whereas differences in P3b amplitude between dyslexic and control participants were found for the shape, pitch and volume discrimination tasks. In light of the high hit rate in all the conditions, one can assume that participants were mostly performing at ceiling. This might explain why P3b differences were not seen in all conditions.

In a similarly characterised sample of dyslexic adults (chapter 5) we failed to find any differences in P3b amplitude to simple phoneme discrimination, even for acoustically similar phonemes (/p/ and /b/). Here, however, dyslexic participants showed a reduction in P3b amplitude compared with controls to relatively large acoustic changes in pitch and volume in a simple discrimination task. Furthermore, behaivoural performance (responses and reaction times) were not different between dyslexic and control participants for pitch and volume detection. The absence of any behavioural differences in these simple auditory detection tasks suggests that the deficits in attention resource allocation observed for these tasks are subtle.

It is quite remarkable that P3b amplitude correlated with reading and spelling performance, particularly in the case of volume oddballs for which there was no correlation with nonverbal measures. This result is consistent with what we found previously using complex phoneme and tone deletion tasks (Chapter 7).

Previous P300 studies have failed to show differences between dyslexic and control participants in the P3b elicited by simple pure tone oddballs. Bernal, Harmony, Rodriguez *et al.* (2000) found no difference in P3b amplitudes in controls and dyslexic children to a 1000 Hz – 3000 Hz pitch discrimination task. Similarly,

Russeler, Kowalczuk, Johannes et al. (Rüsseler, Kowalczuk, Johannes, Wieringa, & Münte, 2002) found no difference in P3b amplitudes in controls and dyslexic adults to a 1000 Hz – 1500 Hz pitch discrimination task. However, Mazzotta and Gallai (1992) did find a reduced P3b in dyslexic children for the same pitch change as the one we used (1000 Hz - 2000 Hz). In comparison to other studies, however, the stimuli used by Mazzotta and Gallai was less than half the duration of that presented by Bernal et al. and Russeler et al. (30 ms tone incorporating a 5 ms rise and fall time). Using a longer 300 ms stimulus, Erez and Pratt found a reduced P3b to verbal (phonetic) but not tone oddballs in dyslexic participants (1000 Hz -2000 Hz). Importantly, none of these studies controlled for possible ADHD co-morbidity in the dyslexic samples involved. A study by Duncan and colleagues (Duncan et al., 1994) found a reduced P3b in dyslexic adults on a visual oddball task (single letters) requiring responses to both deviants and standards, although only a trend for a reduced P3b amplitude in dyslexic participants was observed on a 600 - 1500 Hz pure tone pitch discrimination oddball. Additional analyses showed that the reduced P3b in the visual oddball task was limited to dyslexic participants with the highest ADHD symptom reports. In an earlier study, Holcomb et al. (1986) showed a similar reduction of mean P3b amplitude in dyslexic participants and children with attention or hyperactivity disorders, although the P3b amplitudes recorded in children with hyperactivity were smaller than the amplitudes recorded in dyslexic children and pure attention disordered children.

Separating samples of dyslexic participants scoring high and low on the selfreport measures of ADHD is one way in which the effect of attention disorder on the present P3b results could be examined. However, the abolition of statistical differences in P3b amplitude by separating groups may be the result of a reduction in

sample size and associated statistical power when group sample sizes are as low as 11 per group. The only way forward would be to record data from more participants until sizeable homogenous groups are obtained allowing valid statistical comparisons.

Participants were given all tasks within a modality in the same order. This was required to ensure all participants' received the same amount of practice of the simple discriminations, before sitting the conjunction discrimination. It may be that practice on these initial tasks, which showed reduced P3b amplitudes in the dyslexic participants, was enough to increase the dyslexic participants attentional processing in the conjunction task. As a control for this, a repetition of one of the initial simple oddball tasks could have been run after the conjunction task to examine directly for practice effects. In any case, the overall pattern of performance and ERP differences suggest that the task used in this study may have been too easy to ensure sufficient processing load differences. Ideally, one would need to use a dual (or multi-) feature task which is already demanding for control participants, i.e., which affects behavioural performance significantly. Only then would we expect to see an increased cost in dyslexic participants if our hypothesis of a general attention deficit is correct.

# 8.5 Conclusion

Overall, no perceptual ERP differences (P1, N1, P2) were observed between dyslexic and control participants for the visual or auditory discrimination tasks, whereas a reduced P3b amplitude in dyslexic participants compared with controls suggested differences in attentional processing for shape discrimination, pitch discrimination and volume discrimination. However, dyslexic participants in this sample had significantly higher inattention scores than the control participants. Whether the reduced P3b amplitudes found for the simple discrimination tasks related

to developmental dyslexia or co-morbid inattention deficits is difficult to ascertain. Furthermore, the oddball paradigms used here yielded accuracy at ceiling and may have therefore been insufficiently demanding on attention to show differences between single and dual feature tasks in the visual or auditory modalities. No story sits by itself. Sometimes stories meet at corners and sometimes they cover one another completely, like stones beneath a river. (Mitch Albom (2003), p.11)

# Chapter 9

# **General Discussion**

In chapters 4 – 8, a series of experiments compared some characteristics of auditory and visual processing in dyslexic adults and matched controls using the P300 event-related potential as an index of attentional resource allocation (Kok, 2001; Polich & Kok, 1995). Initial experiments focused on the presence of a deficit in phonological processing, but later experiments tested for the generalization of the deficit to auditory and visual non-linguistic processing.

#### 9.1 Research Summary

Three ERP experiments were carried out to investigate phonological processing deficits in developmental dyslexia. These studies examined both task relevant and task irrelevant attention to phoneme changes before a fourth compared attention to phonemes and nonverbal auditory stimuli (pure tones). Finally, a fifth experiment was implemented to examine for the presence of a non-verbal (general) amodal deficit in attentional resource allocation in dyslexic adults.

In experiment 1, we found that words starting with an oddball phoneme within a stream of alliterated words elicited a P3 modulation in control adults engaged in a lexical decision task, but failed to elicit the same effect in dyslexic adults (Chapter 4). We considered that the small, early (~300 ms) and right-lateralized P3a was elicited by the surprising phoneme change since the alliterated stream created a phonological expectation. The absence of a P3a to phoneme changes in dyslexic participants is consistent with the absence of shifts in attention to these phonological cues. However, this effect could relate either to a deficit in phoneme awareness independent of task demands or to a general attentional resource limitation caused by focusing on an unrelated complex task (lexical decision, which in itself was sufficiently difficult to discriminate dyslexic and control participants; Nicolson & Fawcett, 1994).The second experiment was designed to address this issue.

In experiment 2, dyslexic and control participants focused on the initial phonemes of words and were required to respond to phoneme changes. In this task, since the initial phoneme of words was directly relevant to the task, we found both P3a and P3b modulations, but these were similar in amplitude in dyslexic and control participants (Chapter 5). Even when the phoneme variation was restricted to changes in one phonetic feature (i.e., voicing), behavioural performance and P3b amplitudes were similar between dyslexic and control participants.

Although experiment 1 (Chapter 4) was consistent with a phonological deficit in developmental dyslexia, experiment 2 (Chapter 5) suggested a critical role of attention. Therefore, we attempted to increase attentional demands in experiment 3 by using a demanding phoneme awareness task (phoneme deletion) in which phonological deviants were task-relevant (i.e. we manipulated attentional demands in the primary task rather than automatic shifts of attention to stimuli distracting attention from the primary task as in Chapter 4).

In experiment 3 (Chapter 6), the P3a elicited by correct phoneme deletion (matches) was significantly reduced in dyslexic participants relative to matched

controls. Therefore, increasing the attentional demands of a task in the focus of attention did reveal differences that failed to appear in a simple phoneme identification task (experiment 2). To examine whether this effect was specific to phoneme processing we designed a tone deletion task matched in structure with the phoneme deletion task (experiment 4).

In experiment 4 (Chapter 7), we found P3b amplitude reductions in dyslexic participants for both phoneme and tone deletions consistent with a deficit that is not restricted to phonological processing. Furthermore, P3b amplitude correlated significantly with reading and spelling performance across the entire sample of participants, whether the task was phonological or not. We interpreted this result as a sign of attentional deficit in dyslexia, which could not merely be accounted for by ADHD co-morbidity (since measures of ADHD symptoms were similar for dyslexic participants and controls) and which was not limited to phonological processing. To test whether the deficit could be generalized to the visual modality, we developed a nonverbal oddball paradigm manipulating processing load such that participant needed to attend to one or two stimulus features in order to identify the target correctly within the stimulus stream (experiment 5).

In experiment 5, participants had to detect targets differing from the distracters according to one feature (pitch or volume for tones; form or luminance for shapes) or two features simultaneously. Contrary to our predictions dyslexic adults were significantly impaired in single feature discrimination tasks (i.e., shape, pitch and volume) but performed similarly to controls for the high load (dual feature) conditions, irrespective of sensory modality.

Overall, our results suggest the existence of an attention capacity deficit in developmental dyslexia, which may interact with phonological processing but is not specific to verbal material.

#### 9.2 ERPs and Attentional Processing

Attention is a process essential to perception and is determined by task requirements. It is unclear whether any ERP components specific to attentional processes exist independent of perception (Coull, 1998). The most obvious manifestation of attention in ERPs is the modulation of ERP components determined by task complexity and perceptual load (Escera, Alho, Schroger, & Winkler, 2000; Kok, 2001).

Classically attentional modulation of ERPs have been observed in the N1 range (N100), in the mismatch negativity (MMN), and in the P3 range (P3a and P3b). Modulations of the N1, MMN and P3a have been predominately observed for taskirrelevant stimulus changes (sometimes referred to as novelty effects), whereas the P3b is classically observed during active stimulus discrimination or categorization (Kok, 2000, 2001).

N1 amplitude is thought to index the initial orienting of attention and perceptual processing of stimulus properties (Leppanen & Lyytinen, 1997; Picton & Näätänen, 1987). N1 amplitude is larger when visual and auditory stimuli are attended to relative to when they are unattended (e.g., Harter & Aine, 1984; Hillyard, Hink, Schwent, & Picton, 1973). However, when attention is focused on stimulus change, N1 amplitude also indexes changes in stimulus properties (e.g., pitch changes in auditory stimuli Leppanen & Lyytinen, 1997). Therefore, in classical oddball tasks the effects of attention are confounded by stimulus property changes on the N1

amplitude. Furthermore, the N1 component is modulated by several overlapping independent processes, one of which is the MMN (Näätänen & Picton, 1987). During passive listening to a stream of tone stimuli (standard stimuli) interspersed with infrequent tone changes (novel stimuli), novel stimuli usually elicit N1, MMN and P3a modulations (e.g., Escera, Alho, Schroger, & Winkler, 2000; Escera, Alho, Winkler, & Näätänen, 1998). Such modulations are largely automatic and can be interpreted in terms of distractibility (Sussman, Ritter, & Vaughan, 1999). While modulation of the N1 and MMN are generally regarded as unconscious 'pre-attentive' effects, the P3a is regarded as an index of the conscious shift of attention to a 'surprising' stimulus (Escera, Alho, Schroger, & Winkler, 2000; Escera, Alho, Winkler, & Näätänen, 1998; Squires, Squires, & Hillyard, 1975). The MMN is thought to originate in the difference between an unexpected stimulus and the sensory memory of previous events (Näätänen, 1992). In this context, subtle discriminations between deviant and standard stimuli in an oddball paradigm may elicit an MMN but no P3a modulation, even though they are commonly observed together (e.g., Escera, Alho, Schroger, & Winkler, 2000; Escera, Alho, Winkler, & Näätänen, 1998).

The P3b component is thought to index task-relevant attentional resource allocation and working memory updating (Donchin, 1981; Polich & Kok, 1995; Soltani & Knight, 2000). Results from studies manipulating task difficulty have suggested that P3b amplitude increases with the level of attention required by a task (see also Kok, 2001; Polich, 1987). In contrast, P3b amplitude has been shown to decrease with stimulus discriminability (see Kok, 2001).

In the current series of experiments we found differences between dyslexic and control participants both in the P3a and P3b components. To sum up the above introduction, the P3a and P3b components can be regarded as indices of automatic

change detection/distractibility and target detection/active focusing of attention, respectively, in the context of an oddball paradigm (Goldstein, Spencer, & Donchin, 2002). However, most of our experiments were not based on the novelty effect found in classical oddball paradigms and, therefore, our interpretations need to take into account specific task demands.

# 9.3 Attention Deficit: Impaired Shifts, Limited Capacity or Deficient Automatisation

The proposal of attention deficits in dyslexic children and adults is not new. Studies comparing the attentional abilities of dyslexic and control participants go back to the 1970's (e.g., Pelham, 1979; Pelham & Ross, 1977). However, current theories of attentional limitations vary in which aspects of attention they see as impaired and causally related to reading performance.

Three main attentional deficits have been reported in dyslexic adults and children: (a) An amodal attention deficit selective to rapidly presented stimuli (Hari & Renvall, 2001; Hari, Renvall, & Tanskanen, 2001; Hari, Valta, & Uutela, 1999; Renvall & Hari, 2002), (b) a spatial attention deficit selective to visual stimuli (Buchholz & Davies, 2005; Facoetti, Lorusso, Paganoni, Umilta, & Mascetti, 2003; Facoetti, Paganoni, & Lorusso, 2000; Facoetti, Paganoni, Turatto, Marzola, & Mascetti, 2000; Facoetti & Turatto, 2000; Facoetti, Turatto, Lorusso, & Mascetti, 2001; Roach & Hogben, 2004; Valdois, Bosse, & Tainturier, 2004) and (c) a general skill automatisation deficit (Moores, Nicolson, & Fawcett, 2003; Nicolson & Fawcett, 1990; Nicolson, Fawcett, & Dean, 2001).

Lower performance of dyslexic children and dyslexic adults on rapidly presented auditory and visual stimuli have been predominately interpreted as signs of deficits in perceptual processing (see Chapter 2). However, since low-level perceptual abilities normally differ between modalities, amodal deficits in monitoring rapidly changing stimuli may be better explained by a deficit in the automatic orienting of attention.

Evidence for a deficit in shifts of attention for both auditory and visual stimuli in dyslexic participants comes from a range of studies. In the auditory modality, Helenius, Uutela and Hari (1999) showed that dyslexic adults have higher thresholds for the segregation of alternating tones into two continuous tone streams. One interpretation of this result is that dyslexic adults have a prolonged window of auditory integration, meaning that the identification of rapidly presented tones is impaired by interference from successive tones (Hari & Renvall, 2001). However, Griffiths, Hill, Bailey and Snowling (2003) failed to find any differences between dyslexic adults and controls in windows of auditory stimulus analysis during a rapid auditory backward masking task, even for very short inter-stimulus intervals (20 ms). Furthermore, in the visual modality, Hari, Valta and Uutela (1999) found a prolonged 'attentional blink' for letter identification in dyslexic adults. The 'attentional blink' (AB) refers to a limitation of attention capacity whereby normal participants fail to perceive a second target when it is presented within 400 - 600 ms of a first target in a rapid serial visual presentation (RSVP) stream(Hari & Renvall, 2001; Raymond, Shapiro, & Arnell, 1992). The 'attentional dwell time' taken up by the first target in a RSVP stream is likely to be the result of limitations in attentional capacity (J. Duncan, Ward, & Shapiro, 1994). In contrast to the findings of Hari et al. (1999), Lacroix, Constantinescu, Cousineau et al. (2005) found a reduced AB in dyslexic children compared with controls performing a similar rapid serial detection task. Visser, Boden, Gaischi (2004) found no differences between dyslexic and control children in the classical AB effect, however dyslexic children showed a greater 'blink' than

control children when targets were presented at different spatial locations. Results on the characteristics of the AB in dyslexic individuals have therefore been somewhat inconsistent so far.

Spatial attention may be crucially important to reading performance, since visually perceived words need to be isolated from surrounded distracters (Facoetti, Lorusso, Paganoni, Umilta, & Mascetti, 2003; Facoetti, Paganoni, Turatto, Marzola, & Mascetti, 2000). Spatial cueing performance might therefore index reading performance in dyslexic participants.

In normally developing children, 100 ms intervals between the visual presentation of cue and target stimuli result in an identification advantage to the cued location that is not present for 250 ms cue-target intervals. However, Facoetti, Lorusso, Cattaneo *et al.* (2005) found the reverse pattern in dyslexic children with greater cueing for longer (250 ms) than shorter (100 ms) cue-target delays. Facoetti, Lorusso, Paganoni *et al.* (2003) found the same type of reverse pattern in dyslexic children for targets of different size; whereas large targets normally take longer to identify than small ones at cue-target delays of 100 ms and 500 ms, dyslexic children show no effects of target size for the short delay (100 ms), but do for the long delay (500 ms). In a study similar to that of Facoetti *et al.* (2005), Heiervang and Hugdahl (2003) found impaired cueing for both long (800 ms) and short (100 ms) cue-target intervals in dyslexic participants. However, differences in cue eccentricity may account for the inconsistency between these two studies, since costs associated with shifting attention to the periphery (but not foveal locations) are higher in dyslexic participants than controls (Buchholz & Davies, 2005).

Poor visual search performance in dyslexic children suggests that the spatial distribution of selective attention may be impaired (Facoetti & Turatto, 2000;

Facoetti, Turatto, Lorusso, & Mascetti, 2001). This hypothetical deficit in the spatial distribution of attention is consistent with differences across visual fields. Indeed, distracter interference seems to be less marked in the left visual field than the right in dyslexic participants (Eden, Wood, & Stein, 2003; Facoetti & Turatto, 2000; Facoetti, Turatto, Lorusso, & Mascetti, 2001; Hari, Renvall, & Tanskanen, 2001). Overall, spatial attention deficits may be associated with impaired attention shifting as indexed by poor spatial cueing, rather than visual search strategies *per se* (Roach & Hogben, 2004).

Within the domain of impaired focused attention, it is important to distinguish inattention from distractibility. Although these states are not distinguishable in all tasks, inattention refers to either reduced covert shifts in attention towards a task or insufficient attentional capacity to perform a task, whereas distractibility refers to the inability to inhibit distracters (task irrelevant stimuli) and therefore maintain focus on a task.

By definition the oddball tasks used throughout this thesis all contain distracters and thus require sustained attention. However attentional focus, task complexity and response demands vary between the different experiments (see Table 9.1). In terms of ERP components, P3a amplitude is thought to index distractibility and P3 amplitude attention capacity (i.e., inattention). Since we found reduced amplitudes in dyslexic adults compared with controls for both the P3a and P3b, it could be suggested that attentional deficits in dyslexia involve both distractibility and inattention. However, we feel that this is unlikely. In Chapter 7 we report correlations of P3a amplitude with reaction times across groups, such that P3a amplitude increases with faster response times. If the P3a modulation in the phoneme and tone deletion tasks (Chapter 7) was indicative of increased distractibility, the correlation between

P3a amplitude and response times should have been negative. Furthermore, in the phoneme and tone deletion tasks, targets and distractors were identified on a trial-by-trial basis in the focus of attention and not within a passive oddball stream.

Tasks measuring attention generally tap into either selective or divided attention. Selective attention refers to focusing on a minimal set of targets within a larger set of distracters whereas divided attention refers to performing several tasks simultaneously on the same items. Importantly, a capacity limitation may be misinterpreted as a deficit in attention shifting when more than one stimulus or stimulus property is processed simultaneously. Furthermore, strategic (i.e., voluntary) shifts of attention may compensate deficits in automatic attention shifting, and such changes in attentional resource allocation should be indexed by P3b rather than P3a differences. If this was the case, P3b amplitudes should increase with behavioural performance, which was not the case in our experiments (Chapter 7).

Response	Attention	Distracters	Inhibition	Chapter
Deviant and Standard	Focused	Task relevant	Inhibition of	Chapter 6
			distracters	Chapter 7
Deviant only	Focused	Task relevant	Inhibition of	Chapter 5
			distracters	Chapter 8
No response	Shifts	Task irrelevant	No inhibition	Chapter 4

Table 9.1 - Summary of task complexity for each experiment

Task automatisation is potentially a compensatory mechanism for a limited attention system. In normally developed adults, automatisation increases task performance in dual tasks. However, automatised skills are inflexible and are obviously not available for complex novel (unpracticed) tasks, such as the tone deletion used in experiment 4 (Chapter 7).

Our results are not wholly consistent with a deficit in rapid shifts of attention or a lack of automatisation skills in dyslexia. We found a reduced P3b in phoneme and tone deletion tasks that were (a) not rapid (ISI between primes and targets was 1 s) and (b) performed in the focus of attention. An AB type effect in which attention to the prime would have impaired processing of the target is also unlikely because prime and target onset were separated by more than 600 ms and main differences were found in reaction times rather than accuracy. The AB typically occurs between 400 and 600 ms after the first target is processed. With respect to skill automatisation, performance in the tone deletion task suggests a low level of automatisation for both control and dyslexic participants. However, the amplitude of the P3b elicited by targets was reduced in dyslexic individuals. Since we found attentional deficits in non-spatial auditory tasks, our results can not be accounted for by a deficit limited to spatial orienting of attention (visual or auditory).

Overall, our results suggest a deficit in attentional capacity that affects shifts in attention and possibly automatisation indirectly. Unfortunately, co-morbidity of ADHD symptoms with developmental dyslexia in experiment 5 (Chapter 8) makes it difficult to determine whether the attentional deficit is central or modality specific. However, since numerous studies have reported visual and auditory attention deficits independently, the impairment is likely to be amodal (i.e. a central attention resource impairment).

#### 9.5 Implications for Causal Theories of Dyslexia: A Working Model

Reading is a complex process that is reliant on the interaction of a range of fundamental cognitive systems from perception to motor production. Poor literacy development is likely to be caused by deficits in any of these cognitive processes (Grigorenko, 2001).

Our studies support the presence of a phonological processing deficit in dyslexia. However this deficit is modulated by attentional resources (at least in highperforming dyslexic adults) since it is found for highly demanding phoneme awareness tasks but not simple phoneme discrimination. In addition, this attentional limitation is not restricted to language but occurs for highly demanding non-verbal auditory tasks.

While phonological processing deficits are undoubtedly important correlates of dyslexia, the foundations of these deficits remain poorly understood. No studies have shown specific cognitive deficits that are independent of perceptual and attentional antecedents. Therefore, the hypothesis of an attentional deficit and that of a phonological deficit in dyslexia are not mutually exclusive. On the contrary, reduced auditory attention resources are likely to lead to a deficit in segmentation and manipulation of phonemes. Our results suggest that phonological deficits in dyslexic adults seem to relate more to conscious than implicit phoneme processing, and that reduced efficiency in attending to phonological cues is the result of a general resource limitation.

Returning to models of reading development presented in Chapter 2, a specific attentional deficit is difficult to incorporate. There are however several levels at which attentional regulation can influence reading (see Figure 9.1).



(a) Logographic Phase

(b) Alphabetic Phase

Figure 9.1 – Models of reading development, adapted from Ramus, 2004. Grey areas indicate where attention may affect or even disrupt processing.

In the framework of current major theories of developmental dyslexia, a general attention limitation can explain deficits both in rapid attention shifts and automaticity (see Figure 9.2). It may also account for some characteristics of perceptual deficits in dyslexic children and adults. When perceptual load (i.e., the amount of task-relevant stimulus information) is high, distractor interference is low because full attentional capacity is focused on the perceptual task (e.g., in the context of visual search with large stimulus set sizes). However, when perceptual load is low some attentional resources are free to process distractors which may result in task interference. Importantly, this effect can be distinguished from working memory load

effects, since greater loads on working memory result in greater distractor interference (Lavie, 2005).





A general attention deficit accounting for the outcomes of both the magnocellular and cerebellar hypotheses would not account for differences between dyslexic and control individuals in terms of visual and auditory psychophysical thresholds. Therefore our hypothesis can be tested based on experiments comparing low-level perceptual processing capacity in conditions requiring minimal attention involvement and conditions requiring significant attentional focus, whether due to perceptual load increase or dual task interference.

# 9.6 Limitations and Future Directions

#### 9.6.1 Methodological Considerations

Examining processing deficits in individuals with developmental disorders requires specific methodological considerations. A majority of these relate to the nature of the clinical populations themselves.

## 9.6.1.1 Heterogeneous Samples

Individuals diagnosed with developmental dyslexia generally display a range of weaknesses including visual, auditory and language difficulties (e.g., Solan, 1993). However, these difficulties do not characterize all dyslexic individuals equally (e.g., Ridder, Borsting, Cooper, McNeel, & Huang, 1997; Seymour, 1987). Numerous studies of visual and auditory perception have shown that most deficits are limited to subgroups of the dyslexic participants tested (see Ramus et al., 2003; Skottun, 2001). This brings to bare the proposal that dyslexia is characterized by a number of different sub-types, which can be distinguished based on the most prominent cognitive deficits shown by an individual. Strong sub-type divisions have been proposed on the basis of visual versus auditory deficits and lexical versus sub-lexical deficits (e.g., Boder, 1970, 1973; Castles & Coltheart, 1993; Valdois, Bosse, & Tainturier, 2004). However, these classifications have all failed to account for subtle variations between dyslexic readers, some of whom show elements of each of the proposed sub-types, making sub-type classifications of little explanatory use (M. J. Snowling, 2001).

In an attempt to address the issue of different causal explanations of dyslexia, Ramus, Rosen, Dakin *et al.* (2003) examined visual and auditory perceptual processes, motor processes and phonological skills in the same group of dyslexic

adults. Ramus *et al.* identified phonological deficits in all of the dyslexic participants involved in their study, whereas relatively small proportions showed specific perceptual and motor difficulties. Furthermore, five of their dyslexic participants had phonological difficulties in the absence of any other perceptual or motor deficiencies, suggesting that phonological deficits are sufficient to cause dyslexia independent of perceptual or motor difficulties. However, in a more recent study White, Milne, Rosen *et al.* (in press) failed to find phonological deficits in all their dyslexic participants. Therefore, phonological deficits cannot be considered an absolute core deficit explaining literacy difficulties experienced by all dyslexic adults or children. This is especially true in languages which have a transparent orthography, in which fluency is a better index of dyslexia than phonological skills (Goswami, Ziegler, & Richardson, 2005; Landerl, Wimmer, & Frith, 1997).

Since group variability is one of the main factors determining statistical power, it is possible and even likely that the absence of group differences in some studies have been the result of heterogeneity with the samples used. Indeed, when participants vary greatly with respect to the factors of interest, group differences are often abolished. Therefore, studies of dyslexia should examine individual differences in dyslexic samples as well as factors expected to characterize the group as a whole and therefore changes between groups (Snowling & Griffiths, 2003). Essentially, what characterizes a group may not be indicative of individual performance.

One consequence of these considerations is that studies involving individuals with developmental dyslexia should avoid vague inclusion criteria. Even more important is the fact that subtests used for participant selection/screening should not be biased toward a specific deficit (e.g., phonological awareness) because such pretests would bias the whole conclusions towards a particular hypothesis (e.g., the

phonological hypothesis). Participant screening should therefore always include both measures of verbal and nonverbal processing skills which are sufficiently precise to tap into characteristics of developmental dyslexia but sufficiently general to avoid biasing the dyslexic sample towards a specific weakness, unless of course the aim is to identify subtypes of dyslexia. In our experiments, we were very cautious to include various tests of standardized verbal and nonverbal processing for all participants. Discrepancy between verbal and nonverbal performance on these tests was critical for participant inclusion. Our approach, however, is bound to ignore potential subtypes of developmental dyslexia and may account for inter-experimental variability in the results.

Intra-group variability is particularly important in ERP experiments since inter-individual ERP variations are know to be high amongst normal participants. Essentially, without evidence for similar ERP component amplitudes in some tasks and significant amplitude differences in others within the same sample, considerations on group differences become unreliable. Importantly, the best way to establish the relevance of an ERP component for the study of developmental dyslexia is to test for correlations between its amplitude and performance indices obtained independently (cf. Chapter 7). Interestingly, in this series of studies both behavioural and ERP variability was relatively similar between the control and dyslexic adults (cf. Appendix vi). However, the level of inter-individual variability is still sufficiently large to make group categorization by ERP component amplitudes inefficient (cf. Chapter 7).

#### 9.6.1.2 Deficit Severity and Compensation Strategies

A majority of studies of dyslexia have focused on the performance of young children in the formative years of reading development. It is during this period of development that dyslexia is most evident, with some children beginning to read and others having great difficulty. However, some studies have examined the persistence of literacy and phonological deficits into adulthood (Bruck, 1992; Bruck & Treiman, 1990; Felton, Naylor, & Wood, 1990; Pennington, Van Orden, Smith, Green, & Haith, 1990). Even high functioning dyslexic university students show impairments in reading, phonological processing and short-term memory (Hatcher, Snowling, & Griffiths, 2002) even though these deficits are often within the normal range with regard to the criteria used to identify dyslexia in childhood (i.e. within 1.5 standard deviations of control scores, e.g. Birch & Chase, 2004; Griffiths, Hill, Bailey, & Snowling, 2003).

Here it is important to make a distinction between compensation and deficit severity. Compensation strategies employed by dyslexic individuals are likely to differ depending on the severity of their deficit. Obviously, serious deficits will require more intensive compensation. Therefore, it cannot be excluded that highfunctioning dyslexic adults differ in the initial severity of their literacy difficulties and therefore differ in the amount of compensation needed. This is another source of interindividual variability that requires consideration.

The advantage of examining 'compensated' and to a lesser degree highfunctioning dyslexic adults is that any deficits that remain in these individuals are pervasive and likely to be the core of their literacy difficulties. However, little is understood about the nature of the compensation strategies used to over-come childhood difficulties (Birch & Chase, 2004; Gallagher, Laxon, Armstrong, & Frith,

1996). It may be the case that some processing deficits are the direct result of the compensation strategies employed by high-functioning dyslexic adults (Kershner & Micallef, 1992). This is even more relevant when considering the role of attention, since compensation strategies are likely to involve secondary, covert tasks in addition to the primary task (e.g., reading), making any task a divided attention situation (Nicolson & Fawcett, 1990).

Importantly, compensation strategies and cortical plasticity may be reflected in electrophysiological markers (Duffy & McAnulty, 1990; Kujala et al., 2001). However, in our studies, electrophysiological markers of compensation should mainly show negative rather than positive correlations with reading and spelling measures. Therefore, the positive correlations of P3 modulations with reading and spelling observed in several of our studies support the existence of an attentional impairment in dyslexic adults, rather than differences in compensation strategies. It follows that studies of dyslexic children who have not had time to develop strong compensation strategies are critical to understanding the influences of attentional resource limitations in dyslexia.

#### 9.6.1.3 Causal Inferences

Establishing the existence of specific impairments in developmental dyslexia does not imply a causal relationship between these impairments and reading performance and if such a causal relationship exists, it tells us nothing about its direction. While there is developmental evidence that phoneme awareness in childhood is causally related to later reading performance (e.g., Bradley & Bryant, 1978; e.g., Bradley & Bryant, 1983), no such causal relationships have yet been established concerning attentional capacity.

Studies of acquired attention impairments following brain trauma indicate that pure attentional deficits are sufficient to cause impairments in reading (Shallice & Warrington, 1977; Warrington, Cipolotti, & McNeil, 1993). However, the pattern of reading deficits caused by impaired attention is not the same as that found in developmental dyslexia (Beaton, 2004).

Since cross-sectional designs are unable to establish causality between limited attention (or any other perceptual / cognitive deficit) and reading performance, longitudinal studies must be implemented (Goswami, 2003).

Attention, like any other cognitive process, is affected by experience. Similar to the improvement of phoneme awareness skills with reading experience (Morais, Bertelson, Cary, & Alegria, 1986), reading acquisition is likely to develop specific aspects of attention. Because of their poor reading skills, dyslexic adults have much less experience of reading than other adults of similar general cognitive ability. It is therefore not only important to test developmental samples of children, but also to examine chronological age-matched controls (to control for maturational effects) and normally developing reading-age match controls (to control for effects of reading experience) (Snowling, 2000).

#### 9.6.1.4 Co-morbid Disorders

Developmental disorders frequently coexist with one another (Fletcher, Shaywitz, & Shaywitz, 1999; Gross-Tsur, Manor, & Shalev, 1996), although there is some debate as to whether mixtures of symptoms should be considered as single syndromes (see also Démonet, Thierry, & Cardebat, 2005; Kaplan, Dewey, Crawford, & Wilson, 2001). Nevertheless, the core causal factor(s) in developmental dyslexia should systematically discriminate clinically diagnosed individuals.

Populations of children with autism, SLI, Williams syndrome, dyslexia, and ADHD have all been reported to have deficits in attention (e.g., Bara, Bucciarelli, & Colle, 2001; Biederman & Faraone, 2005; Goldberg et al., 2005; Landry & Bryson, 2004; Lincoln, Lai, & Jones, 2002; Noterdaeme, Amorosa, Mildenberger, Sitter, & Minow, 2001) but what is referred to by attentional processes is not the same in all cases (e.g., autistic children show attention deficits mainly to socially relevant cues, Ceponiene et al., 2003). Overall, it is unlikely that a general attentional deficit can discriminate between these different developmental disorders. Therefore, specific aspects of attention (e.g., selective attention, temporal and spatial divided attention, and perceptual load manipulations) must be investigated more systematically in different clinical populations.

#### 9.6.2 Future Directions

Future experiments could examine the effects of task difficulty and perceptual load on reading performance in dyslexic children and compensated dyslexic adults. Finding a correlation between task difficulty / perceptual load and drops in performance would be a good indicator of a selective attention deficit in dyslexia (although establishing specificity would require investigation in other clinical groups). It would be interesting to investigated further potential interactions between attentional capacity and phonological skills. This can be accomplished by manipulating perceptual load and stimulus intelligibility.

As mentioned earlier, attention is thought to be primarily allocated to stimuli relevant to a task, while any remaining resources are available for distractors (Lavie & Tsal, 1994). Availability of attentional resources can thus be inferred from the cost of distractor interference when perceptual load (i.e., the number of relevant stimuli) is increased. By examining the performance of dyslexic participants making semantic categorizations on written words, we could examine whether the attentional capacity limitation in dyslexic individuals depends primarily on the amount of information to process. Another fundamental parameter influencing attentional resource allocation is task difficulty, which can be manipulated by degrading sensory input (Lavie & de Fockert, 2003). Importantly, degraded stimuli should load less on perception than standard stimuli but disambiguating the stimuli will still require more attention.

Characterizing interactions between perceptual load, task difficulty and phonological processing might prove the most interesting aspect of such work. Perceptual load can be manipulated along with the word-likeness of relevant stimuli surrounding a target (e.g., HOUSE surrounded by strings such as XXXXX, KSRTF, ORKTA, SNEEF, or NOUSE). This would allow interactions between perceptual load and stimulus orthographic/phonological salience to be characterized.

#### 9.8 General Conclusion

Developmental dyslexia is a disorder which manifests in impairments not limited to language, but in tasks of high attentional demands. Here we show that reduced P300 amplitudes discriminate dyslexic adults without ADHD from controls in attentionally demanding verbal and nonverbal tasks.

Overall our findings suggest that high functioning dyslexic adults have a general attention capacity deficit that relates to poor literacy performance. It is therefore important to examine the interaction of perception, attention and phonological processing in dyslexic adults. It is in this interaction that the causal mechanisms of developmental dyslexia are likely to be revealed. Our results suggest at least that an auditory attention deficit is partially responsible for the manifestation of phonological processing deficits in dyslexic individuals and leads to poor reading and spelling performance. It is still unclear however how this observation generalizes to the visual modality, as our results so far were inconclusive.

Future research needs to examine interactions between attention and phonological processing in dyslexic individuals more systematically and, ideally, in a longitudinal context. The question of implicit as well as explicit phonological impairments in dyslexia also remains open, but we hope that the paradigms designed during this PhD will serve as a good basis for future investigations in this field.

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## Appendices

Appendix i – Linguistic Stimuli\* (Chapter 4) Appendix ii – Linguistic Stimuli\* (Chapter 5) Appendix iii – Linguistic Stimuli\* (Chapter 6) Appendix iv – Linguistic Stimuli\* (Chapter 7) Appendix v – Individual Cognitive Assesment Scores Appendix vi – Individual Behavioural and ERP Results Appendix vii – Correlation Graphs

\*Note: Phonetic transcriptions are given in CELEX phonetic transcription code (see Baayen, Piepenbrock & Gulikers, 1995, for IPA equivalents).

## Appendix i –Linguistic Stimuli used in Chapter 4

/b/ /k		k/		/p/	/ <b>r</b> /		
	pseudo-		pseudo-		pseudo-		pseudo-
word	word	word	word	word	word	word	word
baron	b&b@n	candle	k&bdl,	pastry	peIskrI	rabbi	r&daI
basin	belfn,	cable	keIdl,	passage	p&dIdZ	rabbit	r&dIt
ballot	b&d@t	canvas	k&gv@s	parade	p@geId	rainbow	reIgb@U
barrage	b&lA:Z	cancer	k&ks@	parish	p&gIS	ranger	reInv@
baker	beIm0	carriage	k&kIdZ	patrol	p@gr@Ul	radar	reImA:
bacon	beIm@n	campus	k&lp@s	painting	peInkIN	racket	r&pIt
balance	b&t@ns	campaign	k&mleIn	panic	p&bIk	razor	reIb@
baggage	b&nIdZ	cabbage	k&mIdZ	packet	p&mIt	reason	ri:mn,
badger	b&f@	canteen	k&nbi:n	panther	p&nb@	reader	ri:v@
banner	b&l@	carrot	k&n@t	palace	p&nIs	remains	rIbeInz
banker	b&Np@	canal	k@p&l	package	p&pIdZ	regard	rIbA:d
banking	b&NpIN	candy	k&pdI	pattern	p&p@n	regime	reIbi:m
batsman	b&nsm@n	cabin	k&pIn	parking	pA:bIN	relief	rIbi:f
bazaar	b@pA:	canon	k&p@n	parcel	pA:dl,	reserve	rIb3:v
barrel	b&p@l	castle	kA:dl,	parsley	pA:flI	research	rIb3:tS
bargain	bA:bIn	cargo	kA:d@U	parlour	pA:n@	retreat	rIbri:t
barley	bA:pI	carbon	kA:f@n	party	Iq:Aq	regret	rIbrEt
barber	bA:10	carving	kA:qIN	partner	pA:sn@	relic	rEdIk
bathroom	bA:prUm	cartoon	kA:gu:n	patron	peIdr@n	resource	rIdO:s
basket	bA:smIt	carpet	kA:lIt	patience	pelfn,s	resort	rIdO:t
basis	beImIs	carcass	kA:m@s	painter	pelvt@	refuge	rElju:dZ
bearing	bE@dIN	captain	k&stIn	paper	pelk@	revenge	rIhEndZ
beauty	biu:pT	chemist	kEdIst	patient	peIkn.t	reform	rIkO:m
bedside	bEdmaId	cleaner	kli:k@	payment	pelvant	repair	rTIEQ
beetle	bi .ml.	climber	klaId@	peasant	pEbn.t	reverse	rT13:s
belief	bImi · f	climate	klaIvIt	nieces	pi:dIz	reward	rT10:d
bedroom	bEmrIlm	colleague	kObi .a	netrol	pEgral	release	rImi:s
behalf	bInA · f	concert	kObs@t	nension	pEgSn.	report	rTmO:+
beating	bivyIN	collanse	kadens	nelvis	pEgon,	result	rImV1+
bishon	bIdan	clothing	klaudin	neonle	pliml	remnant	rEmy@nt
business	bidep	commerce	kod3.s	people	pr.ml,	remand	rInA.nd
builder	bilf@	convent	kOgy@pt	nenner	pEnor,	recall	rInO:1
building	bIlpIN	contact	kogvenc koltskt	pepper	phile p3.bp	review	rIpiu:
birthday	blipin	combat	kOmast	persont	pg.bn;	revolt	rIpgult
bisquit	bJ.guei bTepTt	cottage	kOmTd7	percent	pedenc	return	rIn3.n
blankot	blspit	costumo	kOcklim	picture	pibtbe	rescue	rEediu.
blossing	DIWNPIC	coffin	kOmTr	pichic	PIRIIR	romark	rT+A.k
blossom	blondm	comfort	kVmp@+	pillow	pide	robot	ralitot
bossom	bliedem	controlt	komtotl	pillow	pideo	ropoint	reolot Tri.t
booking	bubty	cockial	kOnkEst	pilot	parmer	writer	TIVIIC
booking	DODIN PUPIN	contest	kOnses	pigeon	DIUTU	writing	TATOR
bover	DODIL	conscience	konteris	pision	promit,	ridor	ratytN
boxer	DOD26	convoy	konEnt	planet	Predic	rifle	Tarbe
bonus	Deopes	comment	KOPENT	planner	DT&WG	river	raidi,
boarding	NID:00	commune	kopju:n	plastic	PI&MTIK	rivel	LIK6
border	bo:pe	comer	KU: ge	police	perr:s	ribbo	raimi,
moberod	m9q:0a	countroom	kU:prUm	pony	penat	nodali	rinen

bottom	bOn@m	cooking	kUvIN	poison	pOIdn,	rocket	rOdIt
boulder	b@Ulm@	crater	kreIl@	pocket	pOmIt	robin	rOgIn
bowman	b@Uf@n	creature	kri:n0	polish	pOnIS	romance	r@Uh&ns
brandy	br&pdI	credit	krEnIt	portion	pO:dn,	routine	ru:bi:n
breeding	bri:mIN	crisis	kraIdIs	porter	pO:m@	running	rVdIN
briefing	bri:tIN	crystal	krIftl,	posture	pOsg@	rugby	rVgdI
brigade	brImeId	cricket	krIpIt	poultry	p@UlbrI	ruler	ru:k@
brochure	br@Um@	critic	krIpIk	powder	paUb@	runway	rVnkeI
bundle	bVgdl,	crossing	krOdIN	practice	pr&mtIs	rumour	ru:p@
budget	bVldZIt	courage	kVfIdZ	present	prEbn,t	rubbish	rVpIS
butter	bVl@	cover	kVg@	pressure	prEv@	runner	rVv@
bullet	bUpIt	culture	kVlf@	pleasure	plEf@	rental	rEftl,
bunker	bVNg@	country	kVptrI	princess	prIndEs	riot	raI@b
bucket	bVnIt	curtain	k3:pn,	problem	prOgl@m	rubber	rVs@
burden	b3:gn,	career	k@dI@	promise	prOkIs	ruins	rUIpz
butler	bVtp@	keeper	ki:d0	product	prOmVkt	racing	reIfIN
backing	b&fIN	colonel	k3:pl,	process	pr@UpEs	reading	ri:bIN
balloon	b@gu:n	kidney	kIdpI	project	prOvEkt	record	rEvO:d
bamboo	b&kbu:	kingdom	kIfd@m	profit	prOgIt	region	ri:f@n
barman	bA:k@n	kitchen	kIfIn	pudding	pUkIN	reply	rIflaI
bladder	bl&t@	killer	kIt@	pursuit	p@dju:t	railway	reIlkeI
bomber	bOk@	chorus	kO:v@s	purchase	p3:t@s	request	rIswEst
bookshop	bUknOp	copper	kOd@	pupil	pju:tl,	respect	rIsnEkt
bracket	br&fIt	cupboard	kVn@d	public	pVmlIk	response	rIstOns

Re I	/n/	1	m/		/1/	/g/		
word	pseudo-word	word	pseudo-word	word	pseudo-word	word	pseudo-word	
knowledge	nOpIdZ	marine	m@bi:n	landlord	l&nkO:d	garage	g&fA:dZ	
nature	neId@	magic	m&bIk	landing	l&nfIN	gambling	g&mflIN	
navy	neIgI	merit	mEkIt	ladder	l&p0	garment	gA:d0nt	
	neIbn,		m&kSn,	laughter	lA:kt0	garden	gA:pn,	
napkin	n&SkIn	marble	mA:kl,	laundry	10:nbrI	gallon	g&t@n	
native	neIlIv	major	meIv@	labour	leIf0	glasses	glA:dIz	
neglect	nIblEkt	metre	mi:v@	lady		glory	glO:gI	
needle	ni:pl,	meadow	mEp@U	label	leInl,	gossip	gOdIp	
neighbour	neIf@	message	mEpIdZ	leaflet	li:nlIt	goddess	gOgIs	
network	nElw3:k	miner	maIb@	letter	lEk@	golfer	gOlg@	
notice	n@UbIs	mirror	mIp@	lemon	lEk@n	goodness	gUpnIs	
notion	n@Udn,	missile	mIpaIl	lecture	lEvtS@	gravel	gr&dl,	
nonsense	nOks@ns	motor	m@Ug@	living	lIdIN	grammar	gr&g@	
nostril	nOntr@l	monster	mOkst@	lightning	laIdZnIN	greeting	gri:pIN	
nylon	naIdOn	movie	mu:lI	limit	lIfIt	grenade	gr@peId	
nuisance	nju:ln,s	mushroom	mVgrUm	licence	laIg@ns	grouping	gru:tIN	
number	nVlb@	monkey	mVNpI	linen	lItIn		gIbA:	
nursing	n3:tIN	murder	m3:p0	lover	lVb0	gutter	gVp0	

	/b/	/ <b>r</b> /			
word	pseudo-word	word	pseudo-word		
baron	b&b@n	rabbi	r&daI		
basin	belfn,	rabbit	r&dIt		
ballot	b&d@t	rainbow	relab@U		
barrage	b&lA:Z	ranger	reInv@		
baker	beIm@	radar	reImA:		
bacon	beIm@n	racket	r&pIt		
balance	b&t@ns	razor	reIb0		
baggage	b&nIdZ	reason	ri:mn,		
badger	b&f@	reader	ri:v0		
banner	b&10	remains	rIbeInz		
banker	b&Np@	regard	rIbA:d		
banking	b&NpIN	regime	reIbi:m		
batsman	b&nsm@n	relief	rIbi:f		
bazaar	b@pA:	reserve	rIb3:v		
barrel	b&p@l	research	rIb3:tS		
bargain	bA:bIn	retreat	rIbri:t		
barley	bA:pI	regret	rIbrEt		
barber	bA:10	relic	rEdIk		
bathroom	bA:prUm	resource	rIdO:s		
basket	bA:smIt	resort	rIdO:t		
basis	beImIs	refuge	rElju:dZ		
bearing	bE@dIN	revenge	rIhEndZ		
beauty	bju:pI	reform	rIkO:m		
bedside	bEdmaId	repair	rIlE0		
beetle	bi:ml,	reverse	rIl3:s		
belief	bImi:f	reward	rIlO:d		
bedroom	bEmrUm	release	rImi:s		
behalf	bInA:f	report	rImO:t		
beating	bi:vIN	result	rImVlt		
bishop	bId0p	remnant	rEmv@nt		
business	bIknIs	remand	rInA:nd		
builder	bIlf@	recall	rIp0:1		
building	bIlpIN	review	rIpju:		
birthday	b3:gdeI	revolt	rIp@Ult		
biscuit	bIspIt	return	rIp3:n		
blanket	bl&NpIt	rescue	rEsdju:		
blessing	blEfIN	remark	rItA:k		
blossom	blOp@m	robot	r@UtOt		
bosom	bUg@m	receipt	rIvi:t		
booking	bUpIN	writer	raIb0		
booklet	bUplIt	writing	raIgIN		
boxer	bOps@	rider	raIb@		
bonus	b@Up@s	rifle	raIdl,		
boarding	bO:bIN	river	rIk@		
border	p0:b6	rival	raIml,		
boredom	bO:p@m	ribbon	rIn@n		
bottom	bOn@m	rocket	rOdIt		

## Appendix ii –Linguistic Stimuli used in Chapter 5

boulder	b@Ulm@	robin	rOgIn
bowman	b@Uf@n	romance	r@Uh&ns
brandy	br&pdI	routine	ru:bi:n
breeding	bri:mIN	running	rVdIN
briefing	bri:tIN	rugby	rVgdI
brigade	brImeId	ruler	ru:k@
brochure	br@Um@	runway	rVnkeI
bundle	bVgdl,	rumour	ru:p0
budget	bVldZIt	rubbish	rVpIS
butter	bVl@	runner	rVv@
bullet	bUpIt	rental	rEftl,
bunker	bVNg@	riot	raI@b
bucket	bVnIt	rubber	rVs@
burden	b3:gn,	ruins	rUIpz
butler	bVtp@	racing	reIfIN
backing	b&fIN	reading	ri:bIN
balloon	b@gu:n	record	rEvO:d
bamboo	b&kbu:	region	ri:f@n
barman	bA:k@n	reply	rIflaI
bladder	bl&t@	railway	reIlkeI
bomber	bOk@	request	rIswEst
bookshop	bUknOp	respect	rIsnEkt
bracket	br&fIt	response	rIstOns

	/p/	1	g/
Word	Pseudo- word	Word	Pseudo- word
package	p&pIdZ	gallon	g&t@n
packet	p&mIt	gambling	g&mflIN
painter		garage	g&fA:dZ
panic	p&bIk	garden	gA:pn,
parlour	pA:n@	garment	gA:d@nt
patience	pelfn,s	glasses	glA:dIz
pencil	pEnbl,	glory	glO:gI
percent	p@dEnt	goddess	gOgIs
pillar	pId0	golfer	gOlg@
pillow	pId@U	goodness	gUpnIs
pilot	paIm@t	gossip	gOdIp
pistol	pIsml,	grammar	gr&g@
posture	pOsg@	gravel	gr&dl,
powder	paUb0	greeting	gri:pIN
present	prEbn,t	grenade	gr@peId
pudding	pUkIN	grouping	gru:tIN
purchase	p3:t0s		gIbA:
pursuit	p@dju:t	gutter	gVp@

## Appendix iii -Linguistic Stimuli used in Chapter 6

		12	Mismatches	
Prime	Match	PP	PI	PW
score	core	moor	four	zore
skill	kill	pill	bill	vill
skin	kin	win	bin	rin
place	lace	race	face	tace
plane	lair	dare	rare	hain
glare	lane	rain	cane	nair
plate	late	rate	date	nate
slice	lice	mice	dice	kice
flight	light	right	night	vight
climb	lime	rhyme	time	jime
clock	lock	rock	dock	pock
smile	mile	tile	file	lyle
space	pace	case	base	gase
spark	park	mark	dark	tark
speech	peach	leech	beach	deach
spear	pier	tear	beer	zear
spine	pine	mine	fine	gine
sport	port	wort	fort	dort
spot	pot	cot	dot	mot
grace	race	lace	case	dace
brain	rain	lane	pain	tane
brake	rake	lake	fake	pake
gram	ram	lamb	dam	gam
crash	rash	lash	dash	pash
bread	red	lead	dead	gead
greed	reed	lead	bead	veed
grip	rip	lip	dip	fip
broom	room	loom	tomb	voom
steak	take	make	bake	dake
stalk	talk	walk	fork	lork
star	tar	car	far	dar
start	tart	part	dart	mart
stone	tone	cone	bone	done
stool	tool	wall	ball	vall
store	tour	war	door	vore
sweet	wet	net	jet	keat
sweat	wheat	meat	feat	ket
twig	wig	rig	fig	lig
swing	wing	king	ring	ling
switch	witch	pitch	ditch	nitch

Prime	Match	CELEX Phonetic	Prime	Match	CELEX Phonetic
spore	pore	[pO:r*]	stall	tall	[tO: ]
score	core	[kO:r*]	broom	room	[ru:m]
proof	roof	[ru:f]	smile	mile	[mall]
price	rice	[rals]	spine	pine	[paln]
stile	tile	[tall]	fright	right	[ralt]
flame	lame	[lelm]	stake	take	[telk]
twine	wine	[waln]	bloom	loom	[lu:m]
spawn	pawn	[pO:n]	steal	teal	[ti:l]
flake	lake	[lelk]	scorn	corn	[kO:n]
tripe	ripe	[ralp]	brain	rain	[reln]
stale	tale	[tell]	probe	robe	[r@Ub]
tweed	weed	[wi:d]	bride	ride	[rald]
start	tart	[tA:t]	grail	rail	[rell]
clean	lean	[li:n]	spark	park	[pA:k]
brace	race	[rels]	slime	lime	[lalm]
scare	care	[kE@r*]	plane	lane	[leIn]
swipe	wipe	[walp]	sport	port	[pO:t]
snail	nail	[nell]	troll	roll	[r@UI]
stalk	talk	[tO:k]	spike	pike	[palk]
cloud	loud	[laUd]	space	pace	[pels]
prose	rose	[r@Uz]	praise	raise	[relz]
star	tar	[tA:r*]	spool	pool	[pu:l]
stone	tone	[t@Un]	brake	rake	[relk]
clone	lone	[l@Un]	bleach	leach	[li:tS]
tweak	weak	[wi:k]	spout	pout	[paUt]

Appendix iv –Linguistic	Stimuli	used	in	Chapter 7	

Prime	Mismatch	CELEX	Prime	Mismatch	CELEX Phonetic
flare	dare	[dE@r*]	frame	tame	[telm]
trice	dice	[dals]	croup	soup	[su:p]
steam	ream	[ri:m]	brace	face	[fels]
swine	vine	[valn]	grave	wave	[welv]
spoil	foil	[fOII]	crake	bake	[belk]
trike	mike	[malk]	creep	deep	[di:p]
speech	leech	[li:tS]	sneer	beer	[bl@r*]
sweep	keep	[ki:p]	spear	rear	[rl@r*]
stoat	goat	[g@Ut]	flight	sight	[salt]
float	boat	[b@Ut]	groom	zoom	[zu:m]
brawn	lawn	[lO:n]	grime	dime	[dalm]
breed	seed	[si:d]	braid	maid	[meld]
star	bar	[bA:r*]	crouch	pouch	[paUtS]
snail	hail	[hell]	small	wall	[wO:I]
skirt	dirt	[d3:t]	spoon	boon	[bu:n]
gripe	pipe	[palp]	snort	wort	[w3:t]
blaze	haze	[helz]	stove	cove	[k@Uv]
bleep	weep	[wi:p]	train	pain	[peln]
clerk	perk	[p3:k]	bleat	meat	[mi:t]
grail	bail	[bell]	drape	gape	[gelp]
grain	wain	[weln]	smile	file	[fall]

start	cart	[kA:t]	grope	Pope	[p@Up]
plain	main	[meln]	snare	fare	[fE@r*]
floor	moor	[mO:r*]	spool	cool	[ku:l]
scare	bare	[bE@r*]	plate	date	[delt]
blight	fight	[falt]	sneak	peak	[pi:k]
stall	call	[kO:I]	crape	tape	[telp]
scope	rope	[r@Up]	blurb	curb	[k3:b]
stole	pole		creak	leak	[li:k]
spout	tout	[taUt]	creed	deed	[di:d]
blame	dame	[delm]	stone	cone	[k@Un]
treat	beat	[bi:t]	stork	fork	[fO:k]
steed	weed	[wi:d]	swoon	moon	[mu:n]
groan	moan	[m@Un]	gleam	seam	[sim]
aloom	boom	[bu:m]	price	nice	[nals]
droop	hoon	[bu:n]	spike	bike	[halk]
bride	tide	[tald]	stage	rade	[reld7]
spouse	house	[halls]	steel	reel	[ri·l]
creel	neel	[nu00] [ni:l]	stair	lair	[IE@r*]
scoon	loon	[lu:n]	fright	night	[nalt]
creek	week	[wi:k]	snawn	dawn	[dQ:n]
flamo	dame		spawn	fort	
nlane	sane	[gein]	stale	male	[IO.I] [mell]
grado	sane	[sell]	twood	food	[fi:d]
grade	dark		crino	lino	[li.u]
broil	coil		spine	hopo	[lall]
anood	sol	[SOII]	floir	bone	[b@01] [bE@r*]
speed	hurt	[n.u]	lalata	mata	
spun	nun	[no.u]	Slate	male	
grape	nape	[neip]	brute	lute	[luːt] ແລະເພ
class	pass	[pA:s]	probe	lobe	
smear	tear		pride	wide	[waid]
slope	dope	[a@Up]	brood	mood	[mu:a]
scorn	born	[bO:n]	trout	lout	
graze	laze		steal	deal	[al:1]
grate	fate		grace	mace	[meis]
ыоке	јоке	[dZ@UK]	cream	beam	[m:id]
greed	weed	[wi:d]	proof	noot	[nu:f]
brown	down		breach	peach	
store	fore		ciaim	maim	[meim]
twirl	girl	[g3:1]	drake	саке	[keik]
brave	save	[selv]	state	bate	
freak	beak	[bi:k]	spur	fur	[f3:r^]
stalk	walk	[wO:k]	stout	bout	
trope	mope	[m@Up]	brake	sake	[selk]
drain	gain	[geln]	bloom	doom	[du:m]
flail	tail	[tell]	storm	form	[fO:m]
skate	rate	[relt]	groin	coin	[KOIN]
slight	might	[malt]	steer	deer	[dl@r*]
clean	dean	[a:n]	slime	time	
craze	maze	[melz]	snore	bore	[bO:r*]
stile	pile	[pall]	snake	take	[telk]
groat	moat	[m@Ut]	space	lace	[leis]
slave	cave	[kelv]	sleep	beep	[bi:p]
glare	rare	[rE@r*]	clear	tear	[tl@r*]
prime	mime	[malm]	scar	far	[fA:r*]

Appendix v – Individual Cognitive Assesment Scores

[					DAST	DAST	DAST	WRAT	WRAT	WAIS	Digit
Initials	Group	Hand	Sex	age	Reading	Spelling	NV	Reading	Spelling	NV	Span
KH	Control	R	F	18	116	37	4	107	114	16	16
EB	Control	R	F	19	100	32	8	103	97	18	13
EW	Control	R	F	19	108	39	3	112	114	18	17
ME	Control	R	М	18	85	39	6	119	114	24	18
JG	Control	R	F	19	103	35	5	107	106	19	13
MN	Control	R	М	21	119	33	4	111	104	15	20
GA	Control	R	F	20	87	35	7	106	108	16	24
SR	Control	R	F	20	98	35	7	108	111	19	20
RW	Control	R	F	18	108	34	6	119	109	18	12
MS	Control	R	F	20	97	34	6	113	104	22	25
DA	Control	R	М	21	102	34	4	106	104	21	14
RG	Control	R	М	18	94	35	7	114	104	20	17
LR	Dyslexic	R	F	19	103	27	3	109	89	19	18
JC	Dyslexic	R	М	19	86	32	7	109	111	17	13
TH	Dyslexic	R	М	19	110	27	4	107	89	23	19
AC	Dyslexic	R	F	20	91	30	3	104	94	18	17
RL	Dyslexic	R	F	20	86	26	7	99	92	13	10
ST	Dyslexic	R	F	20	93	28	5	97	92	13	24
EJ	Dyslexic	R	F	21	75	28	6	104	99	22	20
JF	Dyslexic	R	F	21	61	30	6	106	101	20	13
RB	Dyslexic	R	F	20	94	30	6	101	87	24	17
RH	Dyslexic	R	F	22	57	19	8	101	79	25	17
RM	Dyslexic	R	Μ	19	113	34	6	107	109	21	12
PP	Dyslexic	R	М	22	87	27	8	92	87	22	14

Table 1 - Individual scores for cognitive assessment measures (Chapter 5)

					DAST	DAST	DAST	WRAT	WRAT	WAIS	Digit
Initials	Group	Hand	Sex	age	Reading	Spelling	NV	Reading	Spelling	NV	Span
NM	Control	R	F	18	121	31	6	121	104	19	15
ER	Control	L	F	20	115	35	7	118	113	19	14
RH	Control	R	F	21	102	29	6	118	94	21	25
NH	Control	R	М	20	100	34	7	113	113	22	21
KA	Control	R	F	19	111	36	7	112	106	17	23
BS	Control	R	F	19	110	39	5	116	111	19	19
FK	Control	R	М	19	123	35	4	121	114	18	13
SS	Control	R	F	19	113	28	6	109	104	19	18
MS	Control	R	F	20	97	34	6	113	104	22	25
DA	Control	R	М	21	102	34	4	106	104	21	14
KS	Control	R	F	19	122	30	3	112	104	9	12
EW	Control	R	F	19	108	39	3	112	114	18	17
AC	Dyslexic	R	F	20	91	30	3	104	94	18	17
CA	Dyslexic	R	F	20	74	26	6	97	104	16	16
EJ	Dyslexic	R	F	20	75	28	6	104	99	22	20
ER	Dyslexic	R	F	24	110	29	5	97	96	15	14
JF	Dvslexic	R	F	21	61	30	6	106	101	20	13
LP	Dyslexic	R	F	18	70	35	8	109	109	22	15
OB	Dyslexic	R	F	21	108	31	7	101	94	21	19
OD	Dyslexic	R	F	18	83	28	7	107	101	24	19
RH	Dyslexic	R	F	22	57	19	8	101	79	25	17
ST	Dyslexic	R	F	20	93	28	5	97	92	13	24
TH	Dyslexic	R	М	19	110	27	4	107	89	23	19
RM	Dyslexic	R	м	19	113	34	6	107	109	21	12

Table 2 - Individual scores for cognitive assessment measures (Chapter 6)

					DAST	DAST	DAST	WRAT	WRAT	WAIS	Digit
Initials	Group	Hand	Sex	age	Reading	Spelling	NV	Reading	Spelling	NV	Span
AM	Control	R	М	22	113	33	7	104	104	17	16
BL	Control	R	F	20	97	32	6	97	96	14	11
DE	Control	R	F	22	119	40	6	115	113	23	15
DR	Control	R	F	27	119	39	3	100	101	21	14
ES	Control	L	М	18	109	28	4	109	111	13	22
GL	Control	R	F	24	117	33	8	113	106	14	14
JD	Control	R	F	20	131	39	6	111	111	24	27
KJ	Control	R	F	23	125	32	3	115	104	12	19
MH	Control	R	М	20	105	36	7	106	104	14	17
NH	Control	R	F	19	92	31	7	107	97	23	14
PM	Control	R	F	18	105	35	5	114	106	21	19
SX	Control	R	F	21	107	33	5	104	108	17	20
EM	Dyslexic	R	F	19	75	28	7	103	101	16	13
EW	Dyslexic	R	F	19	83	26	4	109	94	18	12
MB	Dyslexic	R	Μ	20	62	16	4	92	60	16	19
MR	Dyslexic	R	F	19	76	33	8	105	101	23	18
OD	Dyslexic	R	F	19	83	28	7	107	101	24	19
PP	Dyslexic	R	М	22	87	27	8	92	87	22	14
PT	Dyslexic	L	М	19	68	31	6	89	89	22	14
RD	Dyslexic	R	М	20	101	28	6	97	87	22	17
RS	Dyslexic	R	F	19	70	27	6	105	89	20	19
ST	Dyslexic	R	F	20	48	23	4	92	92	16	13
TL	Dyslexic	R	М	18	54	29	6	86	87	19	10
VK	Dyslexic	R	F	19	68	28	4	100	92	22	11

Table 3 - Individual scores for cognitive assessment measures (Chapter 7)

In the In	0	Hand	0		DAST	DAST	DAST	WRAT	WRAT	WAIS	Digit
Initials	Group	Hand	Sex	age	Reading	Spelling	NV	Reading	Spening	IN V	Span
CL	Control	R	F	19	82	36	6	116	106	22	22
DA	Control	R	М	19	133	35	6	116	118	20	13
DF	Control	R	М	22	102	34	4	106	104	21	14
DS	Control	R	F	19	177	25	5	103	104	21	21
EH	Control	R	F	19	118	37	6	114	116	21	26
EW	Control	R	F	20	108	39	3	112	114	18	17
RJ	Control	R	F	19	85	34	6	112	106	20	17
LH	Control	R	F	25	129	36	8	119	115	24	23
SF	Control	R	F	22	95	34	5	118	108	24	13
SL	Control	R	F	19	95	31	7	116	111	18	18
SS	Control	R	F	20	107	32	2	113	106	11	12
BW	Dyslexic	R	F	19	112	26	5	109	85	21	13
CZ	Dyslexic	R	М	20	95	32	4	106	94	20	18
JH	Dyslexic	R	F	22	68	21	5	97	82	19	16
JN	Dyslexic	R	F	18	87	32	4	109	104	16	10
KK	Dyslexic	R	F	21	80	26	3	111	101	19	13
LR	Dyslexic	R	F	20	103	27	3	109	89	19	18
NE	Dyslexic	R	F	19	68	27	4	112	94	20	13
OB	Dyslexic	R	F	22	108	31	7	101	94	21	19
PC	Dyslexic	R	F	19	59	30	7	103	97	16	13
TC	Dyslexic	R	М	21	107	24	5	108	94	21	12
TL	Dyslexic	R	М	19	54	29	6	86	87	19	10

Table 4 - Individual scores for cognitive assessment measures (Chapter 8)

Appendix vi – Individual Behavioural and ERP Results



Participants (n = 12 dyslexics & 12 controls)

**Figure 1** – Individual P3a amplitudes for all 24 participants at the right central region (Chapter 4).



**Figure 2** – Individual RTs and P3b amplitudes for all 24 participants at Pz. The left column shows the effect for the narrow phonological contrast (/p/-/b/) and the right column the wide phonological contrast (/r/-/g/; Chapter 5).



Participants (n = 12 dyslexics & 12 controls)

**Figure 3** – Individual RT and ERP results for all 24 participants. RTs are shown in the left column for all match and mismatch conditions. P3a effect (match – mismatch amplitude) and P3b amplitude (match) are shown in the right column (Chapter 6).



**Figure 4** - Individual RT and ERP (P2 and N2) results for all 24 participants. Results for the tone deletion are shown in the left column and phoneme deletion in the right column. N2 amplitudes are shown for match and mismatch conditions (Chapter 7).



**Figure 5** - Individual P3a effects (match – mismatch amplitude) and P3b amplitude for all 24 participants. Results for the tone deletion are shown in the left column and phoneme deletion in the right column (Chapter 7).



**Figure 6** - Individual RTs for all 22 participants in the different tasks. Results for auditory tasks are shown in the left column and visual tasks in the right column (Chapter 8).



**Figure 7** - Individual P3b amplitudes at Pz for all 22 participants in the different tasks. Results for auditory tasks are shown in the left column and visual tasks in the right column (Chapter 8).

Appendix vii - Correlation Graphs

i.



**Figure 1** – Correlation graphs for cognitive assessment measures and P3b amplitude at Pz in all 24 participants (Chapter 7). Correlations for the tone deletion are shown in the left column and phoneme deletion in the right column.



**Figure 2** – Correlation graphs for RTs and ERPs (P3a at Fz and P3b at Pz) in all 24 participants (Chapter 7). Correlations for the tone deletion are shown in the left column and phoneme deletion in the right column.



**Figure 3** – Correlation graph for DAST spelling and P3b amplitude at Pz in the visual shape discrimination task (Chapter 8).



**Figure 4** – Correlation graphs for cognitive assessment measures and P3b amplitude at Pz in the auditory pitch discrimination task (Chapter 8).



**Figure 5** – Correlation graphs for cognitive assessment measures and P3b amplitude at Pz in the auditory volume discrimination task (Chapter 8).