Neurophysiological Evidence Of Sensory and Cognitive Deficits In Dyslexia

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December 2003

Thesis Submitted to the University of Sheffield For the Degree of Doctor of Philosophy

Abstract

For those engaged in trying to understand the cause of dyslexia, these are interesting times. There is increasing evidence that dyslexia may result from a deficit in the brain's ability to process general visual and auditory information, which may subsequently contribute to observed language difficulties. While some suggest that this processing deficit is confined to lower perceptual levels, others propose that it extends to higher cognitive levels of attention and learning. So far there is surprisingly little evidence of research wherein both modalities, both processing levels and various stimulus features have been tested in the same set of dyslexics using electrophysiological measures. This was the purpose of this research. In four studies, event related potentials were recorded from dyslexic and control brains during the non-attentive and attentive discrimination of various visual and auditory stimuli. Average dyslexic-control ERP comparisons were made for sensory N1 and MMN waves in the passive, and cognitive P2, N2 and P3 waves in the active response conditions. Dyslexics had attenuated MMNs during the pre-attentive discrimination of changes in peripheral visual field, auditory frequency and rapid auditory sequences but not auditory duration. Moreover, dyslexics had abnormal P2 or P3 waves during the attentive discrimination of all visual and auditory stimuli. Finally, the previously attenuated MMN to frequency discrimination was enhanced after attentive practice. The feature-specific MMN abnormalities suggest a highly selective, multi-modal, perceptual dysfunction in dyslexics, as predicted by the pan-sensory deficit theory. However, the ubiquitous task-related P2 and P3 abnormalities suggest that their deficits also extend to higher cognitive domains, as predicted by the automatization/cerebellar deficit theory. The subsequent MMN enhancement suggests practice-induced improvements in their perceptual acuity. These findings suggest that dyslexia is a multilevel syndrome: the same dyslexics have problems in both domains: visual and auditory, and at both processing levels: sensory and cognitive.

"The real voyage of discovery consists not in seeking new landscapes,

but in having new eyes."

Marcel Proust (1871-1922)

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List Of Abbreviations

AC	Auditory Compound Experiment (Study IV)
AS	Auditory Simple Experiment (Study III)
CR	Conditioned Response
CRT	Choice Reaction Task
CS	Conditioned Stimulus
EEG	Electroencephalogram
EP	Evoked Potentials
ERP	Event Related Potentials
FRFM	Form Resolving Field Measure
FFP	Frequency Following Potential
LGN	Lateral Geniculate Nucleus
MEG	Magnetic Encephalogram
MMF	Mismatch Field
MMN	Mismatch Negativity
MRI	Magnetic Resonance Imaging
PET	Positron Emission Topography
SRT	Simple Reaction Task
SCRT	Selective Choice Reaction Task
TOJ	Temporal Order Judgement
UR	Unconditioned Response
US	Unconditioned Stimulus
VEP	Visual Evoked Potential
VS	Visual Simple Experiment (Study I)
VC	Visual Compound Experiment (Study II)

Acknowledgements

I would like to thank all the children who participated in this research. Their willingness to participate study after study, as well as their patience and humour during each tiring experiment made this research a reality. And their enthusiasm about the scientific implications of each experiment made this research more meaningful.

My deepest appreciation goes to my two wonderful PhD supervisors Rod Nicolson and Angela Fawcett, for their invaluable guidance and direction, their understanding during the tedious stages, their applaud during the triumphant moments, and their innovative and stimulating perspectives and ideas throughout this project.

My immense gratitude goes to my MSc supervisor and mentor Christopher Yeo, for initially recommending me for this project, for subsequently providing his munificent support, insightful advice and painstaking critique throughout.

I would like to offer my sincere thanks to Katie Overy for her very useful input in designing the auditory stimuli; to Pete Furness for his help in designing the visual stimuli; to Mark Moran and Heather Borland for their support in sorting out kinks in the experimental software; to Nicola Styring for her able assistance in running the experiments; and to Peter Trigg for his vital contribution in writing the data analysis program that finally saw this project to fruition.

My greatest debt of gratitude goes to my family for nurturing me physically, mentally and emotionally throughout this academic undertaking. Their selfless and unflinching support, their belief in my ability, as well as their superb example by way of their own professional dedication and achievements is unparalleled.

Finally, my respect and recognition goes to whatever divine faith sustained my stubbornly persistent belief in this project despite all hurdles and moments of despair, and fuelled my unrelenting passion for this fascinating and challenging field.

Chapter 1

Introduction

"The test of a first-rate intelligence is the ability to hold two opposed ideas in the mind at the same time, and still retain the ability to function".

F. Scott Fitzgerald (1896 - 1940)

1.1 Introduction Overview

For centuries, man's efforts to uncover the underlying causes of any neurological disorder had to rely entirely upon two fundamental approaches: meticulous observations by experienced eyes and methodical analyses by inquisitive minds. Now, in the 21st century, neuroscience has been empowered by highly sophisticated structural and functional investigative tools, providing far more powerful "eyes" to assist the human intellect in understanding the sources and mechanisms of the brain's disorders.

This work is concerned with understanding the mechanisms of one such neurological disorder with the aid of one such investigative tool. It attempts to study the specific visual and auditory brain processes underlying 'developmental dyslexia', the most recognised and widespread developmental disorder, with the help of 'event related potentials', one of the most widely used and accurate tools for analysing the speed of these brain processes.

This introductory chapter will provide, firstly, an analysis of the key stages and elements of information processing that have been implicated in each of the three theories of dyslexia; secondly, a systematic description of the main components of event related brain potentials that index each of these processing stages; and finally, a broad outline of the key objectives of the four studies that comprise the subsequent experimental chapters of this thesis.

In addition to the theoretical background presented in this introductory chapter, a section on human information processing has been included in Appendix A. It consists of a description of the terms and definitions for the various components of information processing that are relevant to this thesis, as well as a systematic account of the behavioural methods used to assess the nature and speed of each of these stages of information processing. These concepts are usually implicit and assumed in most literature in cognitive neuroscience, and have therefore not been included in this introductory chapter.

1.2 Dyslexia

1.2.1 <u>Background to Dyslexia</u>

Over a hundred years ago a doctor in England published the first ever description of a disorder that would subsequently come to be known as 'developmental dyslexia'. In a paper entitled 'A Case of Congenital Word Blindness' he wrote, "Percy F aged 14 ... has always been a bright and intelligent boy...and in no way inferior to others of his age. His great difficulty has been - and is now - his ability to learn to read. This inability is so remarkable, and so pronounced that I have no doubt it is due to some congenital defect. He has been at school or under tutors since he was 7 years old, and the greatest efforts have been made to teach him to read, but, in spite of this laborious and persistent training, he can only with difficulty spell out words of one syllable (Pringle-Morgan, 1886).

In that succinct introduction in the British Medical Journal in November 1896, Pringle-Morgan captured the paradox that has perplexed scientists for a century since: the profound and persistent difficulties some very bright people face in learning to read and spell. Until this day a child's reading ability is taken as an indicator of his or her intellectual ability, yet the evidence and experience of countless dyslexics such as Percy F argues strongly against such an assumption. Indeed, individuals of great repute in the fields of science, art and politics - Albert Einstein, Alexander Graham Bell, Leonardo da Vinci, Auguste Rodin, George Washington and Winston Churchill – all of whom are believed to have shown symptoms of dyslexia, have proven beyond doubt, the lack of any correlation between ability and dyslexia.

The term 'dyslexia' was derived from the Greek words *dys* meaning difficult and *lexis* meaning word, by the German ophthalmologist R. Berlin. It has since been officially defined as "a developmental disorder in children who, despite conventional classroom experience, fail to attain the language skills of reading, writing and spelling commensurate with their intellectual abilities" (World Federation of Neurology, 1968).

The qualifier 'developmental' refers to a disorder of suspected congenital or hereditary origin, in contrast to 'acquired dyslexia', a disorder resulting from brain injury after the onset of reading (Frith, 1986).

Developmental dyslexia is now known to be a hereditary neurological disorder that affects a large number of people - almost 5% of the global population (Badian, 1984) - making it the most common and widespread developmental disorder. As society has become increasingly reliant on written information, dyslexia has become more of a problem. In modern Western society, the mastery of the basic literary skills of reading, writing and arithmetic is a necessary prerequisite for success in both school and employment settings, and in society at large. The seriousness of learning and reading disabilities is therefore hard to exaggerate. In describing his feelings about growing up with a learning disability Nelson Rockefeller, vice president of the United States, recalled: "I was dyslexic and I still have a hard time reading today. I remember vividly the pain and mortification I felt as a boy of eight when I was assigned to read a short passage of scripture at a community service and did a thoroughly miserable job of it. I know what a dyslexic child goes through - the frustration of not being able to do what other children do easily, the humiliation of being thought not too bright when such is not the case at all". Dyslexics, therefore, can often be severely handicapped and isolated in a modern world.

Yet, despite its high prevalence and significance, the underlying neurological basis of dyslexia is still not fully understood and is still the subject of much debate and controversy. Hence, a key target for research in dyslexia is to establish its precise nature and cause of this disorder.

1.2.2 <u>Aetiology of Dyslexia</u>

Criteria for Causal Models of Developmental Disorders

In any attempt to understand or explain a developmental disorder, it is useful to define the disorder in terms of different levels of analysis. Uta Frith's well-established causal model of developmental disorders provides a useful framework for any analysis into the aetiology of dyslexia. The model incorporates three levels of description. Stated in Frith's words:

"First there is the biological level, where one may look for causes and cures, using, in the case of these studies, brain-imaging methods to identify physiological deficits. Second, there is the behavioural level, where one can make one's observations and assessments, using in this case, a range of tasks to identify performance deficits. Third, there is the cognitive level, which lies in between and makes links in all directions. It is here that 'the intuitive clinical impression can be captured that the presenting disorder is a distinct and recognisable entity despite variable symptoms" (Frith, 1997).

Processing Impairments Implicated in Dyslexia

The three theories of dyslexia, in their simplest forms, can be considered to differ mainly in the manner in which they implicate the different levels of description and the different components of information processing in the brain. The first theory places the underlying cause of dyslexia in the domain of language, the second in the domain of perception and the third in the domain of learning. Put another way, the first implicates deficits in language acquisition; the second implicates deficits in visual and auditory sensory/perceptual processing and the third implicates general cognitive and motor skill acquisition and information processing. Each will be discussed in detail and, where and when necessary, a further theoretical explanation of the mental processes involved will be provided before the impairment is discussed.

Proposed Theories for the Cause of Dyslexia

There is now a wealth of interdisciplinary information about dyslexia, which has uncovered a vast range of seemingly disparate behavioural deficits observed in this disability. This has led to three well-supported alternative explanatory theories that these deficits, via specific cognitive processing mechanisms, to possible biological causal origins of the disorder.

1.2.3 <u>The Phonological Deficit Theory</u>

The earliest and most widely accepted cognitive explanation of dyslexia, the 'phonological deficit' theory, postulates that the core deficit responsible for dyslexic impairments is phonological, that is, related to the analysis of the sounds in words. In other words, problems with phonological awareness play a causal role in subsequent problems with learning to read.

Background to the Phonological Deficit Theory

In 1973 Isabelle Liberman proposed that the initial obstacle in learning to read lay in developing a phonological awareness (Liberman, 1973). Subsequent work by Liberman, Shankweiler, and their colleagues at the Haskins laboratories throughout the 1970s, and rigorous testing by numerous researchers at various other laboratories and classrooms over the next few decades, established that phonological deficits are present in virtually every poor reader, and that the

problems with phonological awareness play a causal role in reading difficulties (for a review see Brady & Shankweiler 1991).

Phonological Processing and Language Acquisition

The phonological system is part of the language processing system. Phonological processing involves the development and application of 'phonological awareness' or 'phoneme awareness'. Phonemes are the smallest unit of spoken language (vocal sounds) while graphemes are the smallest unit of written language (alphabets). Phonemic awareness is therefore the ability to distinguish or manipulate the sounds within spoken syllables or words.

Phonological Skill in Reading

In some ways it is difficult to understand why hearing sounds has any important part to play in learning to read. Reading involves the use of the eyes, rather than the ears. Indeed, when reading familiar words it is not necessary for skilled readers to use phonological analysis at all. The visual patterns of whole words can be recognised because they have already been laid out in the sight vocabulary. Thus their meaning or semantics, can be retrieved by using a direct visual route from the word to its meaning, without the need to translate the letters into sounds. This is also the strategy that young learners use when they first begin to learn to read. Before they have learnt the alphabet principle that syllables can be broken down into phonemes and matched with letters, they learn to recognize only the whole pattern of the first simple words that they learn; then they associate these directly with their meanings (Stein and Talcott, 1999).

However, a purely visual strategy cannot help with reading unfamiliar words, and most words are indeed unfamiliar to a beginning reader. Learning to read an alphabetic system requires learning the grapheme-phoneme correspondence, that is, the correspondence between the written letters and the constituent sounds they represent in speech. The letters of the word have to be translated into their corresponding sounds. From these the child can reconstruct the sound of the entire word, hence it's meaning. Since 'phonology' is the science of sounds and the knowledge of grapheme-phoneme (letter-sound) correspondences, this strategy is called the 'phonological' route for reading (Ellis, 1993).

Hence, if a child lacks phonemic awareness, he/she will have difficulty learning this letter-sound relationship, and difficulties in applying such relationships to help him/her sound out unknown words. Such children, who perform poorly on phonemic awareness tasks via oral language early on, are very likely to experience difficulties acquiring the early word reading skills that provide the foundation for growth of reading ability at later stages. In fact, phonemic

awareness is one of the most powerful determinants of the likelihood of failure to learn to read and therefore a core factor separating normal and disabled readers (Studdert-Kennedy, 2002).

The phonological theory indicates that dyslexics have a specific problem with the representation, storage and/or retrieval of phonemes, that is, with phoneme awareness. As a result the learning of the grapheme-phoneme correspondence, which is the foundation of reading for alphabetic systems, is affected accordingly. The phonological deficit theory therefore postulates a straightforward link between a cognitive deficit and the behavioural problem (for reviews see Snowling, 1987; Stanovich, 1988; Shankweiler, *et. al.*, 1995).

Evidence of Phonological Deficits in Dyslexia

Behavioural Evidence

Support for the phonological deficit theory comes from evidence that dyslexic children are unable to perform tasks requiring segmenting words into smaller units (syllables and phonemes) even after several months of reading and writing, whereas most children are able to perform such tasks well before reading age (e.g. Snowling *et. al.*, 1986; Miles and Miles, 1990). This indicates that dyslexics perform particularly poorly on tasks requiring phonemic or phonological awareness in the form of the conscious segmentation and manipulation of speech sounds. However, evidence for poor verbal short-term memory (Gathercole and Baddely, 1990) and rapid automatic naming (Denckla and Rudel, 1976) in dyslexics also points to a broader and more basic phonological deficit, perhaps having to do with the quality of phonological representations or their access and retrieval.

The theory predicts that the phonological problems should precede the emergence of reading problems. Indeed, it has been found that those young pre-reading children who have problems with phonological segmentation as well as a lack of sensitivity to rhyme and alliteration are likely to show typical dyslexic problems when trying to learn to read (e.g. Bradley and Bryant, 1983; Lundberg and Hoien, 1989; Olsen, Wise and Rack 1989). Moreover, early training in such exercises has allowed the children to progress at a more normal rate through the early stages of learning to read, thus mitigating the effects of the underlying deficit (Bradley *et. al.*, 1988; Lundberg *et. al.* 1988). These observations are the basis of the widespread use of oral language exercises for the rehabilitation of reading and spelling disorders. Moreover, the resultant improvements provide evidence that phonological segmentation does, indeed, perform a key role in learning to read.

The proponents of this theory believe that the phonological problem is "speech specific": the deficit lies in the transform from analog neural response pattern to digital lexical/phonological representation (Liberman, 1998). Several studies with poor readers have provided behavioural evidence that these deficits are indeed specific to the perception of speech and not attributable to general perceptual or learning deficits. This includes low perceptual performance on speech, but not on non-speech, under demanding conditions; low short-term memory for words, but not for non-verbal sounds or pictures; similar patterns of error in verbal short-term memory, whether words are heard or read, suggesting a deficit in the phonological representation common to vision and audition rather than independent deficits in both modes of input (for details see Mody, Studdert-Kennedy & Brady 1997).

The phonological deficit theory is therefore a theoretically plausible hypothesis that firstly, accounts for the reading related problems of dyslexia; secondly, has received support from direct longitudinal tests in young children; and thirdly, has led to direct benefits in remediation. As a result it became the dominant theory for the underlying cognitive cause of dyslexia (Rack, 1994). In fact, it is on the basis of this theory that dyslexia has, more recently, been defined as "a specific language disorder of constitutional origin, characterised by differences in single word decoding, usually reflecting insufficient phonological processing abilities" (Orton Dyslexia Society, 1994).

Even competing theories acknowledge the existence of a phonological deficit in dyslexia and agree on its central and causal role at the cognitive level. However they have different views about the precise source and nature of the phonological problems at the perceptual or biological level. Whereas the proponents of the phonological theory believe the problem is specific to speech perception, proponents of contending theories account for the phonological deficit through more general perceptual or learning impairments (e.g. Stein and Walsh, 1997; Tallal *et. al.*, 1993; Nicolson and Fawcett, 1990).

Neurological Evidence

At the neurological level, it is usually assumed that the origin of the disorder is a congenital dysfunction of the left-hemisphere perisylvian brain areas underlying phonological representations, or connecting phonological and orthographic representation areas (for reviews see Rack 1994; Snowling 1995).

Anatomical work (Galaburda *et. al.*, 1985; Geschwind and Galaburda, 1985) and functional brain imaging studies support this notion of a left perisylvian dysfunction as a basis for the phonological deficit (Paulesu *et. al.*, 1996, 2001; Shaywitz *et. al.*, 1998; Brunswick *et. al.*,

1999; McCrory *et. al.*, 2000; Pugh *et. al.*, 2000; Temple *et. al.*, 2001; Shaywitz *et. al.*, 2002). Other MRI evidence has revealed that dyslexics with phonological deficits in reading have symmetrical plana temporale, which is not observed in normal readers (Larsen *et. al.*, 1990)

Problems with the Phonological Deficit Theory

The phonological deficit suggests that phonological processing is selectively impaired in dyslexics but other aspects of their language, such as their vocabulary and grammatical skills, are normal. In the words of Maggie Snowling "to the extent that learning to read depends upon phonological skills, dyslexic individuals are impaired. However, aspects of reading that depend more upon semantic processing, such as reading comprehension and exception word reading, can be relatively intact" (Snowling, 2001).

While it is widely accepted that the severe difficulties of dyslexics on phonological tasks such as non-word naming result primarily from poor phonological skills, other studies have shown that many dyslexics do, in fact, have language problems that are not easily explained by impairments in phonological processing. For example, some dyslexics have no difficulty decoding phonetically regular words (such as 'chicken' or 'context'), but substantial problems naming and spelling phonetically irregular words (e.g., island, colonel). These dyslexics end up making what are called 'phonological regularisation errors', mispronouncing or misspelling irregular words by attempting to apply usual phonetic rules (such as 'iland' for island). This suggests that their phonological skills are quite intact. The errors in reading and spelling such irregular words might be better explained as deficits in visual coding, representation, and memory rather than phonological deficits. For instance, it has been found that normal readers with high thresholds (i.e., low sensitivity) for detecting coherent visual motion are more likely than those with low detection thresholds to make false positive responses to visual anagrams in a word/anagram (such as, 'bowl' versus 'bolw') discrimination task (Cornelissen *et. al.*, 1998).

It is therefore unlikely that deficient phonological processes alone can account for the wide array of problems that dyslexics manifest while reading. It is also probable that dysfunction of early visual processes plays some role in their reading problems. One consequence of early visual dysfunction in dyslexia might be to disrupt accurate letter position encoding which is necessary for efficient word decoding and lexical access. Also, because reading is inherently a visual behaviour, any visual deficit would inevitably interact with a linguistic deficit to compound the reading difficulties experienced by dyslexics.

Moreover, another major weakness of the phonological theory is its inability to explain the occurrence, in dyslexics, of deficits that are completely independent of phonological processing: sensory and motor disorders. These deficits are the focus of the two alternative theories of dyslexia and a detailed review of the evidence that led to and supports these theories will be discussed subsequently. It is interesting to note that supporters of the phonological theory typically dismiss these non-phonological deficits as not being part of the core features of dyslexia. They consider their co-occurrence with the phonological deficit as potential markers of dyslexia, but do not see them as playing a causal role in the aetiology of the reading impairments (Studdert-Kennedy, 2002; Snowling, 2001).

In summary, it would appear that phonological awareness is an important part of the explanation of dyslexia but not the full explanation in all cases. This project is mainly concerned with the next two theories, and their ability to explain the phonological deficits within their framework.

1.2.4 The Magnocellular Deficit Theory

The second explanation of the cause of dyslexia, the magnocellular deficit theory, places the mechanism for reading disorders within the domain of perception rather than language acquisition. Moreover, it suggests that the deficit is specifically in the sequencing of temporal aspects of visual and auditory information. This theory is commonly considered to be a combination of two more specific theories, the 'visual deficit' theory and the 'auditory deficit' theory. These shall, initially, be reviewed separately for chronological and logical purposes, and then integrated and discussed as a unified, 'pan-sensory' theory, consistent with contemporary views.

Visual Deficit Theory

This long-standing alternative theory in dyslexia predicts that the core deficit responsible for dyslexic problems is visual. In other words the phonological problem is secondary to a more basic visual problem, which results in orthographical difficulties, i.e., difficulties in the processing of letters and words on a page of text (Lovegrove *et. al.*, 1980; Livingstone *et. al.*, 1991; Stein and Walsh, 1997).

Background to the Visual Deficit Theory

An interest in the potential visual components of dyslexia goes back as early as the first identification of the disorder. Morgan gave it the name 'word blindness' because he believed that dyslexics' difficulty with reading was perceptual and mainly caused by visual confusion. Soon after, in the 1920s, Samuel Orton, another pioneer in the field, used the word 'strephosymbolia' (twisted signs) to describe his theory that an impairment of the visual processes leads to unstable visual representations in dyslexia (Orton, 1925). However, with the advent and popularity of linguistic research in the 1960s, the most widely accepted theory of dyslexia became that it is essentially a language based problem (Stein et. al., 2000). Most researchers favoured the view that it is not attributable to visual deficits and normal and dyslexic children do not differ systematically in terms of visual processing.

However, there have been significant developments in theoretical vision in the 1970s that have been applied to reading, thus providing a more suitable theoretical framework in which to consider the relationship between vision and reading and enable more extensive research to demonstrate the differences between normal and dyslexic readers in terms of visual processing. As a result, in the past 10 years the idea that impaired visual processing contributes to dyslexics' difficulties is making something of a comeback. The following section briefly outlines this more recent theoretical approach to vision that has been usefully applied and tested.

The Visual Transient System

One approach to vision research indicates that information is transmitted from the eye to the brain via a number of separate parallel pathways with different roles and properties, frequently referred to as channels (Lovegrove, 1993). Each channel is specialized to process information about particular features of visual stimuli. Psychophysical research using this approach has identified a number of channels, each sensitive to a narrow range of spatial frequencies (or stimulus widths) and orientations (Campbell, 1974 cf Lovegrove 1993). Spatial frequency or size sensitive channels are relevant to reading because reading involves a processing of both general (low spatial frequency) information and detailed (high spatial frequency) information in each visual fixation. Detailed information is extracted from an area approximately 5-6 letter spaces to the right of fixation, and beyond this information of a general nature, such as word shape, is also extracted (Rayner, 1975 cf Lovegrove 1993). It has also been shown that the different channels transmit their information at different rates and respond differently to different rates of temporal change. Some channels are very sensitive to rapidly changing or moving stimuli and others to stationary or slowly moving stimuli. Similarly some channels

primarily respond to stimulus onset and offset, whereas others respond throughout stimulus presentation.

Such results have led to the proposal of two subsystems within the visual system with different roles and properties. The first is the 'transient system', which is highly sensitive to contrast, low spatial frequencies and high temporal frequencies, has fast transmission times and responds to stimulus onset and offset. The second is the 'sustained system', which has a low sensitivity to contrast, is more sensitive to high spatial frequencies and low temporal frequencies, has slow transmission times and responds throughout stimulus presentation (Lovegrove, 1993)

The Magnocellular System

Anatomical research has now found that the ganglion cells whose axons provide the signals that pass from the eye to the rest of the brain are indeed differentiated into two types, M type and P type cells. Moreover, their axons remain largely segregated and independent throughout the visual system (Galaburda and Livingstone, 1993). The subdivision begins in the retina of the eye and each division projects to different parts of the primary visual area in the occipital cortex via its own private layers in the main relay nucleus called the lateral geniculate nucleus (LGN). It is here that the subdivision is most apparent and was first discovered. Here a total of 10% of the cells comprise the M cell transient system and are called 'magno' cells while the remaining 90% of the cells comprise the P cell sustained system and are called 'parvo' cells. The magno cells differ from the parvo cells morphologically: they are, as their name suggests, noticeably larger, which means that they gather light from and are more sensitive over a larger area, but are not sensitive to form and fine detail. Also the dendritic area or receptive field size of the magnocells is some 500 times larger than the parvocells, enabling rapid membrane dynamics and faster reactions. In addition, they have heavily myelinated axons that conduct signals 10 ms faster than the parvocells, enabling rapid transmission times to the occipital cortex. Consequently the magnocells also differ from the parvocells physiologically, in four different ways: they have higher acuity, lower colour selectivity, lower contrast sensitivity and higher temporal resolution, where temporal resolution is the sensitivity to rapidly-changing or rapidly-successive stimuli. In brief, the magnocells are said to be the 'where' cells and the parvocells, the 'what' cells.

Evidence of Magnocellular Deficits in Dyslexia

The functional segregation of the two pathways, begun in the retina, continues throughout the visual system; even up through higher cortical association areas. Therefore a problem specific

to the magnocellular pathway could originate at any level from the retina to the prestriate visual cortical areas and would be difficult to localise with behavioural tests. However, one advantage of the separation of the visual magno and parvocellular systems is that the sensitivity of either of the two components of visual processing can be assessed with psychophysical tests using stimuli that selectively activate one or the other. Low intensity, low contrast, low spatial frequency, flickering lights and moving targets have all been shown to stimulate magnocellular neurones selectively. On the other hand, colour and fine detail at high contrast are signalled only by the parvocellular system (Merrigan and Maunsell, 1993). In many laboratories, therefore, the sensitivity of the two systems has been compared psychophysically and physiologically in normal readers and dyslexics.

Psychophysical Evidence

A number of perceptual tests have found that the visual responses mediated by the magnocellular system are slightly, but consistently and significantly, impaired in dyslexics when compared with normal readers. Most of these psychophysical tests have used a uniform field sinusoidal grating, described in Appendix A.

Impaired Contrast Sensitivity

One of the best demonstrations of a transient or magnocellular deficit in dyslexics, at the level of stimulus identification, is that of altered contrast sensitivity. Contrast sensitivity refers to the ability to detect a contrast difference of a stimulus and is a measure of the sensitivity to various spatial or temporal frequencies of visual stimuli. The lower the spatial frequency or higher the temporal frequency, the harder the detection of stimulus contrast. For a sinusoidal grating of fixed average luminosity and spatial frequency, the contrast sensitivity reflects the minimum contrast at which the black and white stripes of the grating become just visible, and no longer appear as just a grey image.

Much of the credit for demonstrating that dyslexics have some degree of visual impairment goes to William Lovegrove who applied the static sinusoidal grating contrast sensitivity technique to dyslexics (Lovegrove et. al., 1980). He showed that their contrast sensitivity was abnormally reduced (they needed a greater contrast) at low spatial frequencies of 1 cycle per degree or c/° (when the black and white bars were finely separated by a 1° angle), which is mediated by the transient visual system. However, at high spatial frequencies of 10 c/° (where the bars are coarsely separated by a 10° angle), which are mediated by the parvocellular system, the contrast sensitivity of the dyslexics was actually higher than in controls, thereby indicating that dyslexics did not have a general visual impairment. If the gratings were transient or flickered, the

dyslexics had low contrast sensitivity at high and low spatial frequencies, that is, they needed greater contrast than controls to see gratings of any size. In other words their impaired contrast sensitivity was exacerbated by their impairment in temporal resolution, specifically, their stimulus individuation. On the basis of these selective deficits he suggested that the visual 'transient system' in dyslexics was mildly impaired.

Since that pioneering paper, much more evidence has been obtained in the last two decades which has shown that dyslexics' grating contrast sensitivity is reduced by up to 10 times particularly at short durations, low luminance, low spatial frequencies and high temporal frequencies and this contrast sensitivity deficit may affect 75% of dyslexics, especially those with evidence of an associated phonological deficit (Cornelissen *et. al.*, 1995; Lovegrove *et. al.* 1982; Martin and Lovegrove, 1984; Lovegrove, 1986; Evans, *et. al.*, 1994).

Impaired Flicker Sensitivity

Another, more direct measure of transient processing, at the level of stimulus individuation, is flicker sensitivity. One form of contrast sensitivity in the temporal domain, is the flicker contrast sensitivity. It is a more direct measure of transient system. Flicker sensitivity refers to the ability to detect a flickering stimulus and can be measured by assessing the fastest rate at which the flicker can be perceived, known as the flicker fusion rate or threshold. Using the sinusoidal grating or checkerboard, if the contrast is modulated periodically between zero and a peak value, it will be seen as a contrast-modulated flicker and if the contrast is completely reversed between a phase and counter phase value in a square wave periodic pattern, it will be seen as a counter-phase flicker.

It has been found that the counter-phase flicker sensitivity in dyslexics, particularly of low contrast and low spatial frequency gratings (< 1c/degree) at high temporal frequencies (> 10 Hz) is significantly reduced (Martin and Lovegrove, 1987; Brannan and Williams, 1988; Mason *et. al.*, 1993; Evans *et. al.*, 1994; Flemingham and Jakobson, 1995; Demb *et. al.*, 1998; Slaghuis and Ryan, 1999), as is the critical flicker fusion rate to other flickering stimuli (Talcott *et. al.*, 1998). Interestingly, some studies have found that this contrast sensitivity deficit appears to affect some dyslexia subtypes but not others (Borsting *et. al.*, 1996; Ridder *et. al.*, 1997). Moreover, it has been shown that good readers of all ages and adults show the same pattern of flicker sensitivity across a range of flicker rates (4 to 24 Hz) indicating negligible developmental differences in flicker thresholds. Conversely, poor readers are significantly less sensitive than adults at medium flicker rates than higher or lower rates, suggesting that a sensory deficit, and not a developmental deficit, is mediating the differences between groups.

Impaired Visual Persistence

Another measure of transient processing, at the level of stimulus individuation, is visual persistence. Visual persistence refers to the continued perception of a stimulus after it has been physically removed from sight. It is assumed to reflect ongoing neural activity initiated by the stimulus perception, which persists after the cessation of the stimulus. If two stimuli are presented in rapid succession, the two images will fuse and appear as one single presentation. Visible persistence can then be measured by assessing the temporal separation necessary to distinguish the two presentations, the 'separation threshold'.

In investigations of visual persistence using spatial frequency analysis in the form of sinusoidal waveform gratings, the duration of visible persistence usually increases with increasing spatial frequency (Eden, 1996). However Lovegrove and his colleagues discovered that dyslexic children had smaller increases in persistence duration with increasing frequency. Persistence threshold was found to be up to 100 ms longer at low spatial frequencies and significantly shorter at higher spatial frequencies (Lovegrove *et. al.*, 1980, Slaghuis and Lovegrove, 1985, Lovegrove, 1993). When magnocellular involvement in the persistence task was reduced using uniform field masking, these differences disappeared (Slaghuis and Lovegrove, 1984), which is consistent with a transient system deficit. Dyslexic subjects also have trouble distinguishing the order of two rapidly flashed visual stimuli (May *et. al.*, 1988). In contrast, dyslexics perform normally on tests having normal prolonged stimulus presentations (Lovegrove, 1986).

Impaired Coherent Motion Detection

It has been shown by recording single neurones in the monkey motion area and posterior parietal cortex that a most effective way of measuring the sensitivity of the whole magnocellular system, including both its peripheral pathway and its central components as far as the motion temporal area, is to measure the visual detection of motion, or motion sensitivity using a random dot kinematogram (RDK). This is achieved by finding the proportion of a field of dots moving around randomly which have to move together 'coherently' for the subject to see them moving as a cloud rather than independently in random directions, the 'motion coherence threshold'. This coherent motion can only be achieved if the motion signals are integrated over a wide area, which is a function of the visual magnocellular system (Talcott *et. al.*, 2000). This is considered a more reliable measure of overall magnocellular sensitivity than using grating contrast sensitivity or flicker fusion thresholds (Stein *et. al.*, 2001).

Up to two-thirds of both child and adult dyslexics have been found to be significantly less sensitive to such coherent motion, with 3-4% higher coherence thresholds than normal readers

of the same age (Cornelissen *et. al*.., 1994, 1995). Moreover, this motion coherence deficit is common to all dyslexia subtypes (Ridder *et. al.*, 2001). One study has found that motion discrimination is a more sensitive psychophysical predictor of dyslexia than contrast sensitivity (Demb *et. al.*, 1998). Moreover, it has established a strong correlation between individual differences in coherent motion thresholds and reading rates. The coherence threshold has also been shown to correlate to performance of a lexical decision task, a finding interpreted as a reflection of variations in lettering position encoding: the unselected normal readers who had high thresholds (i.e., low sensitivity) for detecting coherent visual motion were more likely than those with low detection thresholds to make false positive responses to visual anagrams in a word/anagram (e.g., *bowl* versus *bolw*) discrimination task (Cornelissen *et. al.*, 1998). A subsequent study, which also found that dyslexics were less sensitive than controls to coherent motion, found a high correlation between the sensitivity of both groups to the dynamic visual stimuli, dynamic auditory stimuli and non word reading, a measure of phonological awareness believed to be crucial to reading development (Witton *et. al.*, 1998). Conversely, dyslexics have been found to be just as sensitive as good readers in a static form coherence test, which selectively recruits the parvo cells.

Sequential or Temporal Processing

There is little evidence that dyslexics have difficulty with either the detection or identification of a single visual stimulus or several stimuli presented simultaneously, so that the stimuli can be viewed as a single entity. When a number of stimuli are presented sequentially, dyslexics have no difficulty with stimulus individuation if the stimuli are presented slowly. However, the difficulty arises when the visual stimuli change more rapidly or are presented rapidly in succession such that the temporal interval is very brief (Farmer and Klein, 1995). This is evident from the impairments in flicker sensitivity, visible persistence and coherent motion detection. However, although these tests are direct markers of magnocellular function, they require temporal resolution or sequential processing of events over time that involve many identical stimuli and therefore involve more complex numerosity judgements.

But there is also evidence that dyslexics have problems with temporal processing on several other tasks that require much simpler temporal resolution. Several studies have yielded differences between dyslexics and controls on tasks requiring sequential or temporal processing of visual stimuli in all three components of temporal processing: stimulus individuation, temporal order judgement of sequences and discrimination of sequences.

Stimulus Individuation: In stimulus individuation tasks requiring the gap detection of two vertical lines presented sequentially in the same location, dyslexics needed longer ISIs than

controls to reach 75% accuracy, and in tasks using the integration of two or more parts of a stimulus, dyslexics required longer ISIs to perceive two non-identical stimuli rather than one integrated form (for details of studies see review by Farmer and Klein, 1995).

Temporal Order Judgements: There is not much evidence that dyslexics have difficulties in temporal order judgements in the visual domain. One study found that learning disabled children who were 4 years behind in reading had greater difficulty in the order judgements of red and yellow light flashes compared to children who were 2 years behind in reading. In studies involving the presentation of two adjacent stimuli to various sides of a fixation point, with varying stimulus onset synchronies, dyslexics required a greater stimulus onset synchrony to identify which position appeared first and/ or which stimulus appeared first (for details of studies see review by Farmer and Klein, 1995).

Sequence Matching: Dyslexics were found to be impaired in a sequence matching task involving sequences of light flashes with long (1000 ms) or short (500 ms) intervals on cross modal matching tasks involving the matching of dot patterns to click patterns, and the results were correlated with reading skill. In a study involving the presentation of two adjacent words with varying stimulus onset synchronies (SOA), dyslexics required a greater SOA to identify the word that appeared first, and also the position that appeared first. In another study dyslexics were less able to reproduce the correct location and identity of letters when they were presented rapidly in sequence, but no worse than controls when the letters were presented simultaneously, suggesting that it was only with sequential presentation that dyslexics were impaired (for details of studies see review by Farmer and Klein, 1995).

In summary, these psychophysical studies suggest that impairment to the transient system in dyslexics makes them less sensitive to transient stimuli, particularly rapidly-changing (dynamic) or rapidly successive (sequential) stimuli. Even though it is unlikely that deficits in flicker detection, visual persistence or coherent motion detection could result directly in a reading disability, these deficits represent a loss in the temporal resolution of processing, which, in turn, could indirectly influence the reading process.

Physiological Evidence

Electrophysiology

Following a decade of psychophysical studies, the focus turned to electrophysiological work, specifically evoked potentials, perhaps to secure a more objective form of evidence in support of the theory. Some abnormalities had previously been noticed in the morphology and

topography of visual evoked potentials (VEP) in dyslexics, but the method became more sharply focused on the particular problem of a magnocellular deficit.

The most significant observation is the reduced amplitude and latency of the evoked response to low contrast and low spatial frequency stationary sine wave gratings (May *et. al.*, 1991). It has also been shown that the evoked potentials to transient gratings, specifically the contrast reversal of a checkerboard pattern, is significantly different at low contrast and high temporal frequency while responses to lower frequencies and to higher contrast at all stimulating frequencies are all within normal range (Livingstone *et. al.*, 1991; Lehmkuhle *et. al.*, 1993). Another study in favour of both magnocellular and parvocellular deficit has found higher contrast thresholds for the activation of the magnocellular pathway in dyslexic subjects, and suggested that there may be a similar difference in parvocellular pathway activation, though all other studies conclude there is no parvocellular deficit in dyslexics (Ridell and Hainline, 1993). However, one study failed to find any difference that might be interpreted as magnocellular deficiency (Victor *et. al.*, 1993).

Functional MRI

Other studies using the technique of functional Magnetic Resonance Imaging (MRI) have shown that dyslexics have reduced activation of visual area V5/MT, the visual motion area that is dominated by magnocellular input, in response to coherent motion detection using a random dot kinematogram (Eden *et. al.*, 1996; Demb, Boynton and Heeger, 1997).

Anatomical Evidence

Probably the most convincing evidence of a magnocellular deficit is the anatomical evidence of magnocellular abnormalities in the brain. Galaburda and colleagues compared the magnocells in the deep layers of LGN in the brains of five dyslexic brains and five normals, and discovered that the magnocellular layers were more disorganised and up to 27% smaller in the dyslexic brains, but not in the parvocellular layers (Livingstone *et. al.*, 1991). They suggested that the decreased size of the cells might have functional consequences that are consistent with physiological and psychophysical findings, since smaller cell bodies are likely to have thinner axons, which should have slower conduction velocities.

Thus the evidence that many dyslexics do indeed show abnormal development of the visual magnocellular system is now very persuasive, though more detail would be required to evaluate these findings.

Linking Magnocellular and Reading Deficits in Dyslexia

Orthographical Skill in Reading

Learning to read requires, in addition to phonological skill, the acquisition of good orthographic skill. Orthography is the visual analysis of the form of words; hence orthographic skill is the ability to recognise the visual form of words, thus allowing their meaning to be accessed directly.

Therefore any causal connection between magnocellular function and reading requires not just a demonstration of poor magnocellular sensitivity, but also a demonstration that this magnocellular sensitivity predicts orthographic skill.

Magnocellular Dysfunction and Orthographical Skill

It has been found that visual motion sensitivity is a predictor of both reading and spelling ability, so that skilled readers tend to have high visual motion sensitivity, whilst poor readers have low visual motion sensitivity (Witton et. al., 1998). In particular it appears that visual motion sensitivity explains the independent variance in orthographic, but not phonological, skill (Talcott et. al., 2000). A recent study of the visual requirements of orthographic skill revealed a high correlation between visual motion sensitivity in the random dot kinematogram, and the subject's ability to carry out an orthographic task in which the subjects are presented with two words that are phonologically identical but where one is a pseudo-homophone, i.e. incorrectly spelled but sounding the same (Cornelissen et. al., 1998). This correlation applies particularly for irregularly spelt words because reading these successfully requires accurate processing of their visual form. These relationships suggest that motion sensitivity, hence magnocellular sensitivity, controls, in some way, the visual or orthographic skills required for reading.

Beyond the Magnocellular System to the Parietal Cortex

Nevertheless, as pointed out by Stein "correlation does not prove causation" (Stein and Talcott, 2001) and it is still not immediately obvious how and why impairments in visual magnocellular function, particularly impaired temporal processing, can affect orthographic skill and, consequently, reading. The magnocellular impairments that have been found in dyslexics are very mild and usually only demonstrated with low contrasts, flicker, or unusual motion conditions that are not found during normal reading. Since print has a high contrast and does not flicker or move around, the impaired contrast or flicker sensitivity of the dyslexic's

magnocellular system is unlikely to be the direct cause of his/her reading difficulties (Stein and Walsh, 1997). According to the magnocellular theory, the answer probably lies in the anatomical connections from the magnocellular layers of the LGN to the posterior parietal cortex (Stein and Walsh, 1997).

The Posterior Parietal Cortex

One bundle of retinal ganglion cell fibres projects directly to the visual area of the midbrain, the superior colliculus. The superior colliculus is responsible for saccadic eye movements and also receives extensive cortical inputs, particularly from the visual cortex (in the occipital cortex) and frontal eye fields (in the frontal cortex). Another bundle of retinal ganglion cell fibres projects to the visual area of the thalamus, the LGN. The M ganglion cells of the retina project to the two most ventral layers, the magnocellular layers, of the LGN, while the P ganglion cells project to the four dorsal layers, the parvocellular layers. The magnocellular layer in turn projects to a separate layer, 4C, of the primary visual cortex (V1). As discussed earlier, the striking anatomical segregation has led to the view that these separate sequences of retinal ganglion, LGN and visual cortical cells can be regarded as two parallel pathways, referred to as the M and P pathways. These then feed into two extrastriate cortical pathways, the P pathway continues as the ventral pathway or ventral stream and extends to the inferior temporal cortex. The M pathway becomes the dorsal pathway that extends from V1, through areas V5 and MT, the visual motion areas, to the posterior parietal cortex. The posterior parietal cortex then projects to and receives from the frontal eye field, which is involved in selecting targets for upcoming saccades. The frontal eye field in turn projects back to the posterior parietal cortex as well as to the superior colliculus.

Anatomical Relationship between Magnocells and Posterior Parietal Cortex

Anatomical research has confirmed that although much intermingling of the parvo and magno processes occurs in the cortex, the PPC is dominated by magnocell like properties, including sensitivity to direction of movement, sensitivity to direction of gaze and relative insensitivity to colour or visual form (Stein and Walsh, 1997). Slight impairments of the mLGN organisation or performance might, therefore, be multiplied to producegreater deficits in PPC function. The PPC is known to be important for normal ocular control as well as visuospatial attention, both of which are very important components of reading (Morris and Rayner, 1991; Olson et. al., 1991; McConckie et. al., 1991; Pavlidis, 1991). Moreover, damage to this region is known to result in reading disorders (Kinsbourne and Warrington, 1982 cf Stein and Walsh, 1997).

Hence there are numerous areas required to participate in visuomotor control and visual attention both of which are required for the reading process. A key participant involved in this multilevel processing of eye movement control and attention, which receives a large input from the magno cells via the visual cortical areas, is the right parietal cortex (Stein, 1989). It has been argued that this area in particular may be the culprit in dyslexia.

Visuomotor Function

Normal Visuomotor Control

Achieving visual/orthographic skill depends on a person's underlying visuomotor capacity to see letters accurately and in the right order, which, in turn, relies on their eye movement control or visuomotor control.

Types of Eye Movements

There are two main types of eye movements: 'gaze holding' and 'gaze shifting'. The main gaze holding eye movement is 'fixation', which holds the eye still on a target. The three main 'gaze shifting' eye movements are 'saccades', which are short rapid jerky movements that move the eye from one object of interest to the other, 'smooth pursuit', which are longer, slower and smoother movements that keep the eye on a moving target and, 'vergence', which focus the eyes on targets at various depths by enabling each eye to move equal amounts in opposite directions.

Eye Movements in Reading

Three of these eye movements are essential to reading: fixations, saccades and vergence. When reading, the eyes have to move across the text, therefore a series of short (30 ms) 'saccades' have to be made rightwards along the line of print, between relatively lengthy (250 ms) 'fixations', during which the eye identifies individual words by 'convergence' on the point of fixation, which is usually at the normal reading distance of about 30 cm.

Visuomotor Control in Reading

Also, in reading, the eyes are never stationary, so images are constantly smearing across the retina. Yet one's perception of the page remains stationary as opposed to being blurred during the reading saccades. This perceptual stability is achieved by two main visuomotor mechanisms. First, the eyes ignore any motion between successive images unless there is a

motor signal that the eye has moved intentionally: Magnocell activation strongly suppresses the blur of images streaming across the retina that would otherwise be seen. This is known as saccadic suppression. Second, larger unwanted eye movements are controlled and corrected, in a route mediated by the magnocells.

As described above, the magnocellular system dominates the visual projections to the posterior parietal cortex, which is part of the cerebral cortex responsible for visually guided voluntary eye movements, and to the superior colliculus, which is responsible for automatic reflex eye movements. Thus, between saccades, any motion of images on the retina generated by unwanted eye movements are fed back to the ocular motor system by the magno cells and used to reverse any such movements to bring the eyes back on target. This is known as ocular control. The motion signal generated by unwanted movement of the eyes is the main signal that is used to keep the eye steadily fixated on the word being read. Thus the magnocellular system is involved in guiding reading saccades on to their target and in helping them to maintain stable fixation on each word being read before the next saccade is made. Since the eyes spend 90% of the time fixated on a word rather than moving from one to the next, achieving stable eye control between saccades is especially crucial for accurate reading (Stein, 1991 cf Stein and Talcott 1999).

Evidence of Visuomotor Control Deficits in Dyslexics

The original mechanism by which a deficit in the transient system may affect eye movement processes in reading assumed that the onset of transient or magnocellular activity during each saccade erases or terminates the sustained or parvocellular activity of the previous fixation, and therefore helps to separate information encoded during a sequence of different eye fixations (Breitmeyer and Ganz, 1976 cf Cerstnick and Coltheart,). If this information is not separated, forms seen on the previous fixation might superimpose on those derived from the next fixation, and the individual may perceive overlapping letters. This could lead to visual confusion and, in fact, children do complain of visual experiences during reading, which indicate that they may have such problems (Eden *et. al.*, 1994). However it has been shown that magnocellular activity does not inhibit parvocellular activity during saccades (Burr *et. al.*, 1993) hence Breitmeyer's explanation is now considered unlikely.

More recently, John Stein – one of the first advocates of the visual deficit theory - has proposed one way in which a magnocellular deficit might lead to reading difficulty (Stein 1999, 2001). The magnocells project to the superior colliculus and, via the LGN, to the cortical motion area V5 and the PPC, all of which project to the frontal eye fields and all of which are important for the control of eye movements. Thus the magnocellular system plays an important role in eye

movement control, or binocular control. Stein suggests that magnocellular weakness may lead to the unsteady control of eye movements involved in reading (Stein and Talcott, 1999, Stein 2001). This unstable binocular control can take various forms, which are briefly discussed below.

Impaired Fixation

Impaired motion sensitivity due to magnocellular weakness may result in delayed or attenuated motion signals to the motor control areas in the brain, which results in less efficient fixation, which could cause the letter images to move around on the retina. In dyslexics the wobble during attempts to fixate is much more marked (Eden *et. al.*, 1994). Because these movements were not intended, they would not be accompanied by the corollary motion signal discharge by the magnocells indicating that the eyes had moved, that would normally compensate and reverse them and keep the eyes on target. Hence the image movements could easily be misinterpreted as the actual letters moving and their order in a word could become confused, preventing reliable memorized representations of their orthography. This may explain why poor motion sensitivity leads to poor orthographic skill: impaired motion sensitivity due to magnocellular weakness may lead to unstable visual fixation, this causes unsteady visual perceptions, and this in turn interferes with children's ability to acquire orthographic skills (Stein, 1991).

Numerous studies have found that there is a marked tendency for those with poor motion sensitivity to have unstable binocular control and unstable visual perceptions when attempting to read (Stein and Fowler, 1981; Riddell *et. al.* 1990; Eden *et. al.*, 1994; Cornelissen *et. al.*, 1991, 1994).

Impaired Vergence

Again, it is the magnocellular component of visual processing which seems to play the main part in stabilizing the vergence eye movements and helping to keep the two eyes fixed steadily in convergence upon each word, hence enabling maintain stable fixation (Mowforht, Mayhew and Frisby, 1981). A vergence system break down due to magnocellular impairment will cause the eyes to diverge uncontrollably; but since perception is not informed about what has happened, the fusion of the two images provided by the eyes cannot be maintained and fluctuating double vision ensues. Unsteady eye fixation can therefore cause the two eyes' views of the letters to vary from moment to moment and even to cross over each other. Hence the letters can appear to move around and change places so that their order can become confused.

Several studies have shown that the convergence system of dyslexics is significantly less stable and limited in range than that of normal readers, particularly their vergence amplitudes (Stein and Fowler 1993; Riddell, Fowler and Stein, 1987, 1988; Stein, Riddell and Fowler, 1988; Cornelissen et. al., 1993; Eden et. al. 1994; Griffen et. al., 1998).

Thus dyslexic children have demonstrated deficits in both fixation stability and vergence amplitudes. However saccades have been found to be impaired only to the extent that fixation at the end of the saccade is unstable (Eden et. al., 1994).

Impaired Smooth Pursuit

Some researchers have failed to find any of the above mentioned differences in eye movement recordings during saccadic tracking or reading tasks (Black et. al. 1984; Brown et. al., 1983; Olson et. al., 1983; Stanley et. al., 1983) leading to some controversy concerning the role of impaired eye movement control in dyslexia. Also many studies that have found any differences have only focused on eye movements during reading, leaving open the possibility that the reading impairment itself may result in altered scanning patterns. However one comprehensive study was carried out utilizing non-reading tasks that were thought to involve various neural mechanisms (Eden et. al., 1994). It demonstrated that in addition to the fixation and vergence deficits, dyslexics tended to be poorer at 'smooth pursuit', an eye movement not likely to be common during reading. This abnormality, found particularly in the right visual field, was correlated with reading ability. Another study has also demonstrated this difficulty with pursuing a moving target smoothly (Griffin et. al., 1998)

Link between Visuomotor Control Deficits and Reading Deficits in Dyslexics

Since stable binocular control is essential for stable visual perception during reading fixations, unstable eye movement might lead to unstable visual perception or 'visual confusion'. Indeed, dyslexics with unstable binocular control have symptoms which seem to be a consequence of this unstable perception: they complain that words and letters they are trying to read seem to move around, cross over and change places, merge with each other, move in and out of the page, to blur or suddenly get larger or smaller (Fowler and Stein 1979, Stein and Fowler, 1981, Cornellisen et. al., 1998). These are exactly the symptoms one would expect if their two eyes tended to move around independently and unintentionally, causing an unstable visual world and fluctuating double vision. Clearly such visual confusion would make reading difficult. Therefore children with binocular instability tend to make visual reading errors. When they attempt to read unfamiliar words, they sound out the confused and overlapping letters and words that their unstable minds eye presents them with, so that this produces nonsense words instead

of real words (Cornelissen *et. al.*, 1991). In addition, because their visual impressions of words are confused, such children are forced to rely more on the phonological rules that they have learnt. So those with unstable fixation have a characteristic tendency to spell irregular words phonetically, i.e. to make phonological regularization errors (Cornelissen *et. al.*, 1994).

The binocular control and accuracy of visual location of dyslexics is not only considerably worse than that of age-matched controls, but it is also worse than that of younger children with the same reading age as the dyslexics (Stein *et. al.*, 1987; Riddell *et. al.*, 1990). As Bradley and Bryant have pointed out, such a 'reading age match' establishes the direction of causality (Bradley and Bryant, 1985). If poor reading was the cause of poor binocular control, then younger children with the same limited reading ability as older dyslexics should have equally bad eye control. Instead, in several studies it has been found that the younger children had better eye control (Stein 2000). Hence this reading age match strongly suggested that impaired binocular control causes poor reading rather than the other way round. Likewise, studies have found that all children with unstable binocular control, whether classified as dyslexic or not, tended to make more visual non-word errors than children of the same reading age with good binocular control (Cornelissen *et. al.*, 1991, 1994). Again, this suggests that it was their poor binocular control that caused them to make the non-word errors rather than vice versa.

Visual confusion has been addressed in studies looking at eye movement control in dyslexic populations and these studies have confirmed these anecdotal accounts of visual confusion.

Visuospatial Attention

Since magnocellular outputs serve areas other than the ocular control areas, one would therefore expect that dyslexic subjects who show a deficit on low-level psychophysical tasks which tax the magnocellular system would also have deficits on higher-level attentional tasks which do not rely on the properties of mLGN cells but depend upon the functioning of areas whose main inputs originate in the mLGN (Iles, 2000). Put another way, magnocellular deficits should be traceable at later attentional stages of visual processing.

One area where such later processing is known to occur is the posterior parietal cortex (Iles 2000). As described earlier, the posterior parietal cortex is a major output area of the magnocellular system and magnocellular input is important for parietal lobe function (Merigan and Maunsell, 1993). The parietal cortex receives mLGN afferents via V1 in the striate cortex and areas V3 and V5 in extrastriate cortex, and plays an important function in visuomotor control (Iles 2000).

Normal Visuospatial Attention

Another important function associated with parietal visual areas, which is also regarded as crucial in reading, is visual attention (Riddoch et. al., 1990; Atkinson, 1991). In fact there is much evidence suggesting that the information encoded by the magnocellular visual pathway is crucial for spatial attention processing (Johnson and Dark, 1986; LaBerge and Brown, 1989). Accordingly, another proposed causal link from the magnocellular deficit to reading, via the parietal cortex, involves the regulation of automatic attention in dyslexia (Hari et. al., 2001).

As discussed earlier, the cognitive operation that allows the selection of a particular area of the visual field where the processing of relevant information is facilitated, and also the inhibition of laterally distracting information, is known as 'spatial visual attention'. This involves two additional components attention focusing and attention orienting.

Normal Visuospatial Attention in Reading

To read an unknown word, a sequence of visual symbols must be recognised and transformed into a sequence of sounds via what is known as the non-lexical route of reading. At the same time, to be read correctly, a familiar word must be isolated from the others in the text, via what is referred to as the lexical route of reading. In both cases, what is crucial is the ability to, firstly, move attention from one point to the next, from one word to the next and, secondly, to adjust attention from a distributed or diffused modality to a more focused modality in order to select the relevant information while excluding the irrelevant information (Facoetti 2001).

Thus it follows that the ability to orient the focus of attention spatially (attention orienting) as well as the ability to control its size (attention focusing) are both cognitive processes that are deeply involved in reading (Morris and Rayner, 1991). Such visual spatial attention appears to be critically dependent upon the magnocellular system and the parietal cortex (Posner, 1980; Lawler and Cowey, 1987; Arguin, Joanette and Cavanaugh, 1993).

Evidence of Visual Spatial Attention Deficits in Dyslexics

Recent studies seem to demonstrate the existence of a specific attention disorder in dyslexia (Ackerman et. al., 1990). Dyslexics have been shown to be impaired on a range of visual attention tasks, most of which depend on parietal cortex functioning, particularly those seen following damage to the parietal cortex (Iles, 2000). Attentional deficits have been demonstrated in a developmental dyslexic that mirrors those seen in acquired dyslexia

associated with parietal cortex damage (Valdois *et. al.*. 1995). Children with poor vergence control show evidence of impaired right posterior parietal function (Stein, Riddell and Fowler, 1989), and patients with a damaged right posterior parietal cortex (PPC) show markedly impaired vergence control (Fowler *et. al.*, 1989).

Impaired Attention Focusing

Visual spatial attention is brought about by various mechanisms, the most essential of which is attention focusing. Attentional focusing appears to comprise two independent mechanisms that play a role in adjusting the spatial size of the focus of attention: one exogenous or automatic, and one endogenous or voluntary. When a new object suddenly occurs in the visual field, the focus is first automatically fitted to it, and then an effort has to be voluntarily exerted to maintain attention in the focused mode (sustained attention).

In particular, visuospatial attention is demanded in, and therefore often tested using visual search. Visual search task is an experiment used to study form perception, in which subjects must detect a target stimulus amidst a background array of distracter stimuli, in a briefly presented display. Visual search can involve parallel search, where all the items in the display are processed simultaneously, and only one primitive physical feature is being searched, or it can involve serial search, where each item is examined separately one by one to determine whether or not is has the required conjunction of physical features, and so the search time is longer and increases with the number of distracters. Thus this process involves, in addition to eye movement control, some kind of sustained attentional focus, which is limited in that it cannot encompass the entire field at once. Such serial visual search has been found to relate to reading performance.

It is important to note that in addition to attention focusing, visual search tasks also enable the testing of other aspects of attentional processing such as perceptual grouping, inhibition of irrelevant stimuli and target recognition. Furthermore, all of these functions may be considered as necessary contributors to reading, yet deficits in any one of these functions can be accounted for without invoking language problems (Facoetti *et. al.*, 2001; Casco *et. al.*, 1998; Williams and Bologna, 1985).

Dyslexics have been found to be impaired on a number of visual search tasks. These include tasks that do not induce reading-like strategies, such as visual inhibition (Rayner *et. al.*, 1989) and perceptual grouping (Facoetti, *et. al.*, 2001) as well as tasks that incorporate components of reading, including target identification that corresponds to letter or word identification and stimulus inhibition or perceptual grouping of unattended letters or words (Williams, Brannan

and Lartigue, 1987; Ruddock, 1991). Moreover, it has also been found that those dyslexics with a motion coherence deficit were also impaired on visual search tasks while dyslexics with normal motion coherence performance were unimpaired, suggesting that dyslexics who have visual problems related to magnocellular functions also have visual problems related to the functions of areas such as the parietal cortex, which are dominated by inputs originating in the magnocellular LGN. Moreover, these dyslexics were impaired on serial but not parallel search tasks, indicating that the deficit was specific to the functions related to reading.

It is suggested that the incapability to demonstrate sustained attention might be linked to the disorder of ocular fixation, during which visual information is retrieved in order to decode the written text, which could affect reading, by not allowing exclusion of laterally distracting information (Iles, 2000).

Children with dyslexia also show deficits in other spatial tasks. Several studies have revealed that dyslexics are much less accurate at determining the sequence of small drawings of objects such as fruits, counting the number of dots presented in temporal sequence (Eden et. al., 1995) and at deciding whether two lines are oriented at the same angle in the line orientation sensitivity task (Eden et. al. 1996) and at perceiving a line growing from left to right, or vice versa.

Children with low magnocellular function as evidenced by reduced motion sensitivity, are slower and make more errors in judging the correct order of letters in words when viewing briefly presented neighbouring letter anagrams such as 'rain' versus 'rian' (Cornelissen, 1997). This problem applied not only to letters but also to any visual target in any context. Hence children with reading difficulties and binocular instability, in the form of unstable control of vergence eye movements, are less accurate at localizing small dots presented on a computer screen (Riddel Fowler and Stein, 1990).

Impaired Attention Orienting

Another important mechanism involved in visual spatial attention is attention orienting, which consists in moving the focus across the visual field toward a target. There are two kinds of attentional cues: peripheral cues, consisting in a peripheral abrupt visual onset which is assumed to draw attention to its position exogenously, that is without taxing cognitive processes (Posner and Cohen, 1984), and central cues, which are able to direct attention to a given position only endogenously, that is by means of an act of will by the subject. Since central cues require more controlled cognitive processes, they may be impaired when a subject is engaged in other cognitively demanding tasks, such as actively carrying a memory load (Posner and Cohen,

1984). There is also evidence that the two orienting mechanisms rely on different neuroanatomical structures: the exogenous mechanism seems to be controlled by the parietal lobe, whereas the voluntary mechanism seems to be controlled by the frontal lobe (Posner and Petersen, 1990).

The act of shifting or orienting attention to one side of the visual field facilitates the selection of information on that side of the visual field and the inhibition of information in the contralateral visual field (Facoetti et. al. 2001). This can be achieved by spatial cueing tasks. In these subjects are first cued with the likely spatial location of a target and then respond as rapidly as possible when the target appears at any location in the display. Thus attentional problems result in delayed responses to the spatial cue, particularly when the target appears in a non-cued location. Reaction times are generally faster in the valid than in the invalid condition and this is called the cue effect. (Facoetti and Molteni 2001) Also, neuropsychological studies have shown that unilateral damage of the posterior parietal cortex selectively affects contralateral target detection in the invalid cue condition (Petersen et. al.. 1989; Posner et. al.. 1984, 1987). Its underlying neural mechanisms are involved both in the selection of competing visual stimuli and in related activities such as reading (Inhoff et. al.. 1989; Posner and Rafal 1987).

Dyslexics have been found to perform abnormally on spatial cueing tasks, specifically the Posner task (Brannan and Williams, 1987; Facoetti, 2001). Moreover results have shown that dyslexics have a specific difficulty in attention shifting caused by peripheral cues at short SOAs that are used to elicit automatic orienting of attention, and are also able to maintain 'attention focus' for short periods of time only, presumably not enough for efficient visual processing. However dyslexics have no disability in attention shifting caused by central cues at long SOAs that are used to elicit voluntary covert orientation of attention. Such results support the suggestion that visual selective attention deficits in disabled readers may be due to a specific difficulty in automatic attention orienting and attention focusing. It is therefore possible that the processing speed of stimuli in dyslexics is normal once attention has been allocated to them, but that this allocation takes longer than usual.

It is suggested that the deficit of 'automatic' orienting of attention could affect the planning of ocular movements, which are crucial for reading.

Impaired Attention Dwell Time

Usually a subject, after identifying a target, is unable to shift attention and is blind to other targets within the next 400-600 ms, because the previous target ties up the attentional resources (Duncan et. al., 1994). This period is sometimes referred to as 'attentional dwell time' (Hari

2001). Such a control of automatic attention shifting is attributed commonly to the parietal lobe (Posner and Raichle, 1994). Moreover, it has been demonstrated that cues that preferentially excite the magnocellular pathway predominantly capture visual attention (Steinman *et. al.*, 1997), thereby suggesting that activation of the magnocellular system is important for the efficient regulation of such attention shifting.

One measure of attentional dwell time is the duration of 'attentional blink', the time required, after recognising one target, to identify another in close temporal succession. It was found that the attentional blink was 30% longer in dyslexic adults than normal reading controls (Hari *et. al.*, 1999). Thus a target captures attentional resources for considerably longer time in dyslexics than control subjects.

It has been proposed that suggest weakened magnocellular input in dyslexics may result in selective parietal dysfunction, particularly, an increased attentional dwell time, so that it takes longer for dyslexics to disengage their attention from the previous target and shift it to the next one. As a result, they have a more prolonged 'cognitive integration window' within which subsequent stimuli may interfere. This observed prolongation could significantly contribute to the sluggish temporal information processing of dyslexics (Hari *et. al.*, 1999).

Left Neglect

One possible marker of parietal lobe dysfunction is a spatially asymmetric distribution of visual attention, that is, a right-sided bias in selecting and processing visual information. This is known as 'left neglect' and it has been clinically demonstrated following lesions to the right parietal lobe.

Interestingly, in many of these attention focusing and orienting tasks, dyslexics made more errors in locating targets in the left as opposed to the right visual hemifield (Stein *et. al.*, 1989, Riddel, Fowler and Stein, 1990, Hari *et. al.*, 1999) thereby suggesting a milder version of 'left neglect'. Indeed several studies have shown that in dyslexics greater attentional resources are available in the right visual field than in the left visual field (Hari and Koivikko 1999; Facoetti and Turatto 2000) and that such resources are concentrated (narrow focus) in the left visual field, whereas they are excessively diffuse (wide focus) in the right visual field (Facoetti and Molteni 2001).

In addition to exhibiting a visual field asymmetry in the gradient of spatial attention focus, children with specific reading disorder also show an asymmetric hemispheric control of spatial attentional orienting. During exogenous orienting, a greater cue effect has been observed in

dyslexics in the left visual field that is absent in the right visual field and during endogenous orienting, slower reaction times have been recorded in the left visual field than in the right (Facoetti et. al., 2001).

The significant right visual field advantage observed in all these visual attention tasks indicates that dyslexics may fail to establish fixed hemispheric specialization, in other words, the temporal processing in dyslexics is asymmetric and impaired in left relative to right visual hemifield. This has been referred to as left 'mini neglect' (Hari 2002).

Studies have shown that the tendency to draw clocks showing signs of left-sided distortion is much more common in reading-disabled children than in normal readers (Eden, Stein and Wood, 1991). This is similar in character to the spatial hemineglect seen after right parietal lesions (Iles 2000). Children with poor vergence control show evidence of impaired right posterior parietal function (Stein, Riddell and Fowler, 1989), and patients with a damaged right posterior parietal cortex (PPC) show markedly impaired vergence control (Fowler et. al., 1989). One study (Valdois et. al., 1995) has also report attentional deficits in a developmental dyslexic that mirror those seen in acquired dyslexia associated with parietal cortex damage (Kinsbourne and Warrington, 1962; Behrman et. al.., 1990).

It has been demonstrated that lesions to the right parietal lobe often result in contra-lesional neglect (neglect in the laterally opposed visual field), whereas lesions to the left parietal lobe rarely lead to corresponding impairments. Indeed, the attentional blink may prolong even four fold in left side neglect due to damage of the right posterior lobe (Husain, 1997). Thus it is possible that a diffuse functional disruption of the magnocellular pathways would first be seen as a right visual field advantage, and a left side mini neglect could emerge as a result of decreased magnocellular input to the parietal cortex.

The importance of right parietal lobe dysfunction for deficits encountered in dyslexia is also emphasized by a recent functional MRI study in which the right intraparietal sulcus was activated consistently in an attentional blink task (Marois et. al., 2000). The right intraparietal sulcus thus seems important for capacity-limited attentional processing of visual information.

This demonstration of mini neglect is mild, and hence its direct consequence on the subjects reading and other performance may be minor. However, as the most widely accepted indicator of parietal damage, its existence is in line with the magnocellular deficit theory and, consequently, selective parietal lobe dysfunction in dyslexics.

Impaired Peripheral Vision

Another aspect of visual processing associated with the parietal cortex is peripheral vision, the processing of stimuli in the periphery of the visual field. A large body of evidence has suggested that aspect of vision is impaired in dyslexics, further implicating parietal cortex dysfunction in this disorder (Geiger and Lettvin, 1997; Spinelli *et. al.*, 2001).

It is important to note that peripheral processing, like attention focusing, orienting and shifting, is a good example of a visual deficit that cannot be accommodated within a purely phonological framework of reading impairments.

Since this aspect of visual processing is the focus of one the electrophysiological studies in Chapter 2, thus the evidence for this deficit shall be discussed in more detail in Section 2.2.1 of that Chapter.

Link between Visual Attention Deficits and Reading Deficits in Dyslexics

Written language has existed for a relatively short time, thus it might not reasonable to assume innate brain mechanisms for reading. However, parietal lobe supports several visuospatial functions that are important for reading. Covert attention and saccade control involve the activation of common areas in the parietal, frontal and temporal lobes (Corbetta *et. al.*, 1998) and these two functions are closely related: one first has to shift attention to the target location before a saccade can be made towards it (McPeek *et. al.*, 1999). Learning to read involves training of rapid attentional shifts, associated with eye movements, along the sequential letters and words along a line (Vidyasagar, 1999). In this process, the integrity of the parietal lobe seems essential.

Thus, in summary, the magnocellular deficit could directly impair purely sensory functions such as contrast sensitivity, flicker sensitivity and motion sensitivity, and the consequent hypofunction of the parietal lobe could result in impaired visuomotor control as well as impaired spatial distribution of attention and sluggishness of attentional capture and shifting (Hari *et. al.*, 1999; Merzenich *et. al.*, 1993; Facoetti *et. al.*, 2000; Facoetti and Molteni, 2001).

1.2.5 Auditory Processing Deficit Theory

This theory proposes that the core deficit responsible for dyslexic problems is auditory. In other words, the phonological impairment is secondary to a more elementary auditory impairment,

which results in difficulties with processing certain acoustic features of the phonemes in words (Tallal, 1980; Tallal *et. al.*, 1993).

Background to the Auditory Processing Deficit Theory

Investigations into the potential auditory components of dyslexia began with Paula Tallal and her colleagues in 1970, with a view to understanding the severe deficits in both phonological perception and production that characterised most learning impaired children. They reasoned that "before studying speech, it would be important to assess the integrity of the component acoustic processes that are critical to the analysis of the complex acoustic spectra of speech"(Tallal, 1993). In other words, it is clearly important to determine that a child can hear normally before interpreting deficits in their ability to process or produce speech. And even where it can be shown that the sensory organ is intact, it is still important to assess other central aspects of auditory processing to ensure that the fundamental components of acoustic analysis throughout the nervous system are intact and functioning normally (Tallal *et. al.*, 1993).

With this premise in mind they began by developing a hierarchical battery of tests for assessing the sequential processing of acoustic events, testing the detection, discrimination, individuation, association, rate processing and serial memory for two or more stimuli.

Evidence of Auditory Processing Deficits in Dyslexia

Psychophysical Evidence

Impaired Discrimination of Temporal Features of Sounds

In three basic studies from which all later work ensued, Tallal tested learning impaired children on a task where they were required to replicate the temporal order of two tones presented in rapid succession, at ISIs of 8-305 ms (Tallal and Piercy, 1973). The learning impaired children did as well as the controls on the detection, association and sequencing of the tones at ISIs of 428 ms and longer, however, their performances deteriorated rapidly with shorter ISIs. A similar pattern of results was demonstrated on a task where they were required to say whether the two tones were the same or different. Thus even when the overt ordering judgement was not required, the ISIs involved in the task were too short to preclude the learning impaired children from correctly perceiving and judging the elements of the temporal sequence.

This suggests that at rapid rates of presentation learning-impaired children are significantly worse in their ability to both discriminate and sequence auditory stimuli. Moreover, the data suggests that when given sufficient input time for signal processing, learning impaired children are able to utilize central auditory processes for discrimination and sequencing of sensory information normally. However, they need orders of magnitude more time between the inputs of basic sensory events in order to access these higher-level processes.

Tallal also found that learning impaired children were impaired in a three stimulus serial memory task at 75 ms durations, but were the same as controls when the stimulus duration was lengthened to 250 ms. Moreover, severe deterioration was observed in their performance at sequence lengths above three elements, even with longer stimulus durations.

This indicates that even though increasing the stimulus duration improved the serial memory performance of the learning impaired children, their serial memory remained impaired in comparison to controls.

The time available for acoustic processing is clearly important for sequential memory performance. However, since increasing stimulus duration did not completely remove the deficits in serial memory for tone sequences for learning impaired children, the impairment of serial memory may be independent of the deficit in processing rapidly presented stimuli, such that each stimulus is presented for very brief periods of time, the temporal processing deficit. Conversely, given the developmental nature of language impairment, it is possible that a primary temporal processing deficit may result in a form of auditory deprivation that in turn alters the neuronal mapping and connections across the auditory system with cascading effects on other higher-level auditory processes. The effects of this deprivation may result in, among other things, retarded development of complex serial processes such as auditory serial memory as well as deficit in the perception of rapid and sequential transients within speech.

Subsequent research has provided considerable evidence that dyslexics are impaired at the temporal (sequential) processing of auditory stimuli. In tone fusion tasks, dyslexics and learning disabled children have been found to require longer ISIs than normals to separate two tones, and are affected by tone intensity but not frequency (McKrosky and Kidder, 1980; Helenius et. al., 1999). Similarly in click fusion tasks, dyslexics and learning disabled children have been found to require longer ISIs to separate two clicks and, additionally, the fusion intervals are highly correlated with consonant discrimination (Haggerty and Stamm, 1978; Llinas et. al., 1988). Moreover, dyslexics perceive an illusion of saltatory sound source movement at much longer sound intervals than control subjects (Hari et. al., 1996).

Early non-verbal acoustic studies of Tallal and other researchers clearly showed that learning impaired children exhibited a profound deficit in processing rapidly presented acoustic information. Hence the focus of research turned to address the question of how such a basic temporal integration dysfunction could undermine speech and language development.

The results of the psycho-acoustic studies pointed to an area of temporal dysfunction within the tens of milliseconds range. This time frame implicated difficulties in the discrimination of acoustic events in speech signals occurring within this time frame, that is, at the phonemic level of speech processing. For example, vowels transmit the same acoustic information throughout their spectra and are thus referred to as steady state. Stop consonant syllables such as /ba/, /da/, /pa/ on the other hand have a transitional period during which the frequencies (called formants) change very rapidly over time. Information carried within these brief formant transitions is critical for syllable discrimination.

Tallal investigated the ability of learning impaired children to detect, associate and sequence these two pairs of speech sounds and found that they were unable to reproduce the temporal order of speech sound sequences when consonant-vowel syllables were used as the stimuli, but were unimpaired in performing the same task with steady state vowel stimuli. In order to determine whether the poor performance derived from an impaired ability to process transitional elements on auditory information itself or was due to an inability to resolve other brief duration cues typically found within phonemes, they repeated the same study using computer generated speech stimuli whose spectral or temporal characteristics had been systematically manipulated with the initial 40 ms formant transition within each of the consonant-vowel syllables synthetically extended to 80 ms. The dyslexics were found to be unimpaired in processing the consonant-vowel syllables.

Since then, similar observations have been made with reading disabled children using pure tone pairs, consonant-vowel pairs and vowel pairs (Tallal, 1980; Reed, 1989). On both temporal order judgement and same-different judgement, the reading disabled children were impaired as ISIs decreased for tone pairs and consonant-vowel pairs, but not impaired on tasks involving vowel pairs.

Moreover, dyslexics, as well as pre-readers who were shown to be relatively poor readers in later testing, were found to be impaired in the discrimination of the phoneme pairs pa/ta (deWierdt 1988). Dyslexics were also found to be impaired in temporal order judgements of the consonants p/s within a cluster, even when the ISI was expanded, but were the same as controls

when the two stimuli were artificially slowed. Their performances, especially on the slowed condition, were found to correlate with several tests of phonological processing (DeMartino 2001).

They concluded that a primary inability to process acoustic information that enters the nervous system in rapid succession (within the time frame of tens of milliseconds) will serve to disrupt or delay the development of phonological processes and subsequently lead to more global delayed development of language.

Tallal and colleagues were able to correctly classify 98% of children as normal or language impaired on the basis of six variables involving rapid perceptual and production abilities (Tallal *et. al.*, 1985). Indeed, many dyslexics with or without obvious oral language involvement also manifest rate-processing problems (Tallal 1980; Wolff, 1993; Tallal *et. al.*, 1995; Stein and Walsh, 1997).

Impaired Discrimination of Transient Sounds

The work of Tallal, Farmer and Klein and subsequent researchers has proved controversial because there is some disagreement over whether her test really assesses the processing of rapid changes within an acoustic stimulus, or whether it tests the ability to judge the order of rapidly presented acoustic stimuli, since the former might correlate with the rapid temporal processing required for phonological identification of phonemic features but the latter probably would not.

Therefore such research makes it important to appreciate the distinction between 'rate of perception' and 'perception of rate' in order to define a 'temporal processing deficit' (Studdard-Kennedy and Mody, 1995). Perception, and by extension, processing, can be said to be temporal only when it depends upon the detection of the temporal properties of a long duration stimulus – i.e. 'perception of rate' - rather than the perception of stimuli with short durations or short inter-stimulus intervals - i.e. 'rate of perception' (Talcott *et. al.*, 1998). Put another way, when the defining features of a long duration stimulus are changing with time (as in dynamic stimuli) this measures the 'processing of rate' and when two or more brief stimuli are rapidly presented (as in sequential stimuli) or have spectral changes over a very short time (that is, tens of milliseconds), this measures 'rate of processing' (Williams and LeCluyse, 1990).

Based on this distinction, the sensitivity of dyslexics to auditory transients has been tested using simpler stimuli that unequivocally require transient processing (Witton *et. al.*, 1998). Such measures might provide a more direct test of temporal processing ability that can also be plausibly linked to underlying neural sensitivity. Accurate detection of dynamic stimuli in the

visual domain is likely to depend upon dorsal stream structures with a predominance of dorsal stream input.

A recent study tested dynamic stimulus detection in dyslexics by testing their processing of frequency modulation in sound (Witton, et. al., 1998). The detection thresholds for FM of a tone were measured at three different rates: 2 Hz, at which all subjects could track the changes in the pitch of sound; 40 Hz (the highest modulation frequency necessary for accurate perception of speech), at which frequency changes are perceived as roughness; and 240 Hz, at which subjects detect the presence of a tone at the pitch of the modulating frequency (a perceived component not present in the spectrum). The perception of these modulations reflects different FM processing mechanisms. At 2 Hz and 40 Hz the perception depends on the temporal aspects of the stimulus, whereas at 240 Hz it depends upon spectral cues. The results revealed that the FM detection thresholds in dyslexics were significantly higher for both 2 Hz and 40 Hz FM whereas the detection thresholds for 240 Hz FM were not different between dyslexics and controls. Since the FM detection deficits appear to be specific to slower modulations in frequency, this suggests that dyslexics have difficulties in detecting the temporal modulation of the stimuli rather than the tonal cues, which are perceived at higher modulation rates. These findings also suggest that different auditory mechanisms are responsible for the detection of low and high frequency modulation.

Using both psychophysical and physiological techniques studies have found that adult dyslexics are less sensitive than controls to AM of white noise bursts at modulation rates above 10 Hz (McAnally and Stein, 1996). These findings, together with those on FM, suggested that dyslexics may be generally impaired at detecting slower modulations, i.e., at rates below the critical modulation frequency, where the first pair of spectral side bands falls beyond the width of a single auditory filter. Deficits in detecting both FM and AM may therefore be co morbid in some individuals and could result from the effects of common factors such as the attentional demands of processing slow auditory changes.

However, a recent study measured detection thresholds for both FM and AM sensitivity in the same adult dyslexics and controls, using both high and low modulation rates (Witton et. al., 2002). Furthermore it examined whether individual differences in modulation sensitivity predicted performance on a measure of pseudoword reading accuracy, a sensitive indicator of phonological reading skill, which taps what is generally accepted to be the core deficit associated with reading. It was found that dyslexics were significantly less sensitive that controls to 2 Hz FM but not to 240 FM, as was found in the previous study by the same researchers, (Witton et. al., 1998) and less sensitive to 20 Hz AM but not to 2 Hz AM. The absence of a difference for 2 Hz AM suggests that dyslexics may not have a general impairment

in processing all slow modulations. Moreover, the detection thresholds for both 2 Hz FM and 20 Hz were independent predictors of pseudoword reading ability, suggesting that certain components of auditory processing of modulations are related to phonological decoding skills whereas others are not.

Impaired Discrimination of Spectral Features of Sounds

McAnally and Stein investigated the temporal coding of acoustic stimuli in dyslexics (McAnally and Stein, 1996). As dyslexics have been shown to be poor at discriminating between rapidly presented acoustic stimuli, they first estimated auditory temporal resolution using gap detection. The temporal threshold for detecting interruption of a white noise stimulus was found to be normal in dyslexic subjects at around 2 ms, indicating unimpaired neuronal coding of stimulus onset and offset. However they found that dyslexics were significantly worse at detecting small changes of frequency of pure tones around 1 kHz. This difference suggests that dyslexics are impaired at generating or decoding discharges that are phase-locked to the fine structure of the acoustic stimuli. This conclusion was supported by a further observation that dyslexic subjects were also markedly impaired in binaural masking level difference, that is, in detecting audibility changes of a tone when the phase was inverted in one ear. This mechanism depends on the ability to use the differences in interaural phase, the temporal code of which is converted to a spatial code in the medial superior olive. Furthermore, both measures of phase sensitivity - frequency level and masking level difference, were correlated with reading ability. McAnally and Stein suggested that dyslexics may be impaired in generating phase locked discharges, possibly in the anteroventral cochlear nucleus, in decoding them in the medial superior olive, or in exploiting the resulting spatial code at higher levels of the auditory system.

A subsequent study tested whether the difficulties in discriminating rapidly presented sound sequences might be caused by the impaired neuronal phase locking to the envelopes of the sound stimuli (Hari et. al., 1999). Two stimuli types were used: ~1 kHz sinusoidal pure tones, which produced a spectral pitch due to place coding in the cochlea, and ~80 Hz amplitude modulations of white noise, which produced periodic pitch based on temporal information only. The dyslexics were found to be significantly less accurate that the control subjects in discriminating both spectral and periodicity pitch stimulus, but their performance was not worse in the periodicity task, which would have been the case if it were also due to a specific deficit in phase locking. These results suggest that impaired neuronal phase locking might not explain the problems dyslexics face in processing rapid sound sequences. The difficulties of dyslexics in identifying rapid sound sequences would have to emerge at some other level, for example in a short term buffer where successive sounds can interfere with percepts of the previous and following sounds within a few hundred millisecond 'cognitive integration window'.

These findings were supported by subsequent study in which the performance of poor adult readers was tested on a variety of simple auditory tasks including tone detection, gap detection, frequency discrimination, intensity discrimination, formant discrimination, tone sequence identification and interval discrimination (Ahissar et. al., 2000). The performance of poor readers was found to be impaired on the tasks requiring spectral distinctions, the simplest of which was pure tone frequency discrimination, even without temporal constraints. Adding such constraints, particularly when explicit categorization was required, introduced further difficulties for poor readers. Also, performance in intensity discrimination, with the same task structure, was not impaired, indicating that the source of difficulty was not in general, auditory short-term memory. Moreover, performance on formant discrimination was highly correlated with both reading and pure tone frequency discrimination (Ahissar et. al., 2000).

Impaired Left Hemisphere Specialization

Neurological accounts of dyslexia usually ascribe at least some of the symptoms observed to a left hemisphere dysfunction. It is now widely believed, as a result of numerous and diverse studies, that speech is processed and produced preferentially by the left cerebral hemisphere. Support for this is derives both from studies of adults who have sustained selective brain damage leading to specific functional disorders, and from studies designed to evaluate differences in information processing within and between cerebral hemispheres in normal intact subjects. There is also strong support from various studies that phonological perception and production is primarily specialized in the left hemisphere. A number of studies have addressed whether the processes that have been interpreted as being hemispherically specialized for speech may in fact be specialized, more generally, for the analysis of rapidly changing sequential acoustic information (Tallal 1993).

One study looking at speech processing in adults with acquired brain lesions found that adult aphasics with left hemisphere brain damage showed deficits in discriminating rapidly changing non verbal acoustic information as well as speech sound contrasts that incorporated brief, rapidly changing temporal cues, but were completely unimpaired in the discrimination of other speech sounds that had longer duration steady state or more slowly changing acoustic spectra. Furthermore, there was a highly significant correlation between the language impairment and rapid sequential processing (Tallal, 1993).

It has been found that when competing verbal information is presented to the two ears, subjects more often respond correctly to the information presented to the right, as compared to the left, ear. This right ear advantage has been hypothesized to result from the right ear having primary

access, via contralateral pathways, to the left hemisphere and this preferential processing of speech information presented dichotically to the right ear has been used as strong evidence of left hemisphere specialization for speech perception. One study found a significant right ear advantage for the dichotically presented syllables with 40 ms duration formant transitions, but no such advantage when extended duration formant transitions were presented dichotically, thus demonstrating that the left hemisphere may be specialised for processing rapidly changing temporal information rather than speech per se.

Moreover, visual nonsense letters were presented to either the right or left visual hemifield, and adults showed superior performance in responding to the temporal order of two briefly presented visual stimuli when the stimuli were presented to the right visual field (left hemisphere) as opposed to when the stimuli were presented to their left visual field. These data taken in combination with the dichotic listening results support the hypothesis that the left hemisphere is better equipped to process temporal events that converge in the nervous system within tens of milliseconds, regardless of sensory modality, and regardless of whether the stimuli are verbal or non-verbal.

These findings have been supported further by PET studies in which the area Brodmann 45 in the left frontal cortex was significantly activated only by the sets of stimuli that incorporated rapid acoustic change (Tallal et. al., 1993). In another MRI study it was found that LI children failed to show the expected cerebral asymmetry in the frontal and parietal regions and the degree of aberrant asymmetry was highly correlated with deficits in processing rapidly presented tone sequences (Tallal et. al., 1993).

Physiological Evidence

A large body of physiological evidence has accumulated to suggest problems in the three main aspects of auditory processing discussed in the earlier section. fMRI and electrophysiological studies have demonstrated that dyslexics have impairments in rapid sequence discrimination (Nagarajan 1999; Temple et. al., 2000; Ruff et. al., 2002), in the discrimination of temporal features of sounds (Schulte Korne, 1999; Kujala, 2000) and frequency discrimination (McAnally and Stein 1996, Baldeweg et. al., 1999; France et. al., 2000). Since these aspects of processing are the focus of the two auditory studies described in Chapter 3, physiological evidence for these deficits shall be discussed in more detail in that chapter.

Neurological Evidence

Underlying Neurological Impairment

The original version of the auditory theory made no particular claim at the biological level, but it is now specified within the magnocellular theory.

A separate system of magnocellular neurones similar to those found in the visual pathways has not been identified in the auditory system. Nevertheless each of the auditory subcortical relay nuclei has anatomical divisions similar to magnocellular divisions (Stein and Talcott, 1999). Moreover, recent evidence suggests that these 'magnocellular type' neurones are specialized for tracking rapid frequency and amplitude changes in acoustic signals (Trussell, 1998; Stein and Talcott, 1999). Thus, these neurones may play a role in temporal analysis of sounds that is analogous to that in the visual system. Since the accurate tracking of acoustic amplitude and frequency transients is essential for identifying the phonological cues that characterize speech, it is possible to that impairments in phonological processing may be caused at least in part, by some defect in their auditory 'magnocellular system' (Stein and Talcott, 1999).

This 'magnocellular type' division of the auditory relay in the thalamus, the medial geniculate nucleus (MGN) has been shown to be disorganised, particularly on the left side, in post mortem brains of dyslexics (Galaburda, Menard and Rosen, 1994).

Linking Auditory Deficits and Reading Deficits in Dyslexia

Phonological Awareness in Reading

As described earlier, learning to read an alphabetic system requires learning the 'grapheme-phoneme correspondence', that is, the correspondence between the written letters and the constituent sounds they represent in speech. This in turn necessitates good 'phoneme awareness', that is, the ability to distinguish or manipulate the smallest units of sound within spoken syllables or words. If a child lacks this awareness, he/she will have difficulty learning the letter-sound relationship and, consequently, difficulty learning to read.

Therefore any causal connection between auditory deficits and reading requires a demonstration that this auditory deficit predicts phonological skill or phonemic awareness.

The way in which a failure to correctly represent short sounds and fast transitions would cause phonological difficulties, in particular when such acoustic events are the cues to phonemic contrasts, has been discussed in an earlier section. However it will be summarized again, below in the context of a selection of studies that have examined this causal relationship in more detail.

The results of Tallal's early psycho-acoustic studies indicated a temporal dysfunction in the time frame of tens of milliseconds, and this implicated difficulties in the perceptual discrimination of elements of the speech signals occurring within this time frame, that is, at the phonemic level of speech processing. In fact, although vowels are steady state stimuli and transmit the same acoustic information throughout their spectra, stop consonant syllables do indeed have a transitional period during which the frequencies change very rapidly over time, and the information carried within these brief formant transitions is critical for syllable discrimination. Tallal and subsequent researchers in the last three decades have found that dyslexics are unable to reproduce the temporal order of speech sound sequences when such consonant-vowel syllables are used as the stimuli, but are unimpaired in performing the same task with steady state vowel stimuli. Moreover, when the initial formant transition within each of the consonant-vowel syllables is synthetically extended, dyslexics are unimpaired at processing them, suggesting their poor performance derives exclusively from an impaired ability to process transitional elements and not other brief duration cues typically found within phonemes. Several subsequent studies, discussed in earlier sections, which required dyslexics to discriminate many different speech sounds based on a variety of temporal and or spectral cues suggest that dyslexics are impaired in their ability to integrate brief acoustic components of information occurring within tens of milliseconds in the ongoing speech stream. Furthermore, it has been shown that intensive training of language-impaired children with temporally stretched speech improves their language ability (Merzenich *et. al.*, 1996; Tallal *et. al.*, 1996).

Indeed, there is evidence that dyslexics may have poorer categorical perception of certain contrasts, particularly for items situated close to the inter-categorical boundary, especially articulatory oppositions such as /ba/ and /da/, or sometimes voice onset oppositions such as /ba/ and /pa/ (Manis *et. al.*, 1997, Mody *et. al.*, 1997; Adlard and Hazan, 1998; Serniclaes *et. al.*, 2001). Thus inadequate representations of phonemic units resulting from such auditory deficits could prevent dyslexic children from using and normally manipulating phonological information, thus impairing their ability to acquire the phonological prerequisites to learning to read.

Transient Auditory Stimuli and Phonological Skill

Moreover, several studies mentioned earlier have demonstrated that dyslexics are only impaired at distinguishing rates of frequency modulation that are used for phoneme detection (Witton, 1997, 1998). The success of dyslexics at distinguishing much higher rates of FM shows that they are not simply bad at all auditory tasks, and strongly suggests that they have specific

problems just with the modulations that are crucial for distinguishing letter sounds. In fact, the auditory FM and AM sensitivity in readers was compared with their ability to read nonwords and the correlation between the two turned out to be strikingly high (Witton *et. al.*, 1998, Talcott *et. al.*, 1999, 2000). These relationships were examined further in dyslexics by testing how far their FM sensitivity predicted variance in phonological abilities independently of orthographic ability and it was found that their FM sensitivity continued to account for nearly 25% of the variance in their phonological skill.

Hence, the auditory deficit theory provides a direct cause, in the course of development, of the phonological deficit, and hence of the difficulty in learning to read.

1.2.6 <u>Global Magnocellular or Pan-Sensory Deficit Theory</u>

Although the auditory and visual theories have been presented here separately for historical and logical reasons, their supporters now agree that visual and auditory disorders in dyslexia are a part of a more general pan-sensory deficit.

Background to the Pan-Sensory Processing Deficit Theory

The pan-sensory processing deficit, also referred to as the magnocellular deficit, is a unifying theory that attempts to integrate all the visual and auditory findings mentioned above. It postulates that the magnocellular dysfunction is not restricted to the visual pathways, but is generalized to all modalities, visual and auditory as well as tactile. Hence the deficit is pan-sensory – it affects processing in multiple sensory modalities.

It was suggested when it was realized that an important similarity between visual and auditory deficits is that they are most apparent when dyslexics are required to process rapid sequential and temporal information in either domain (Stein, 1994; Tallal, Miller and Fitch, 1993).

Beyond the evidence pertaining to each of the theories described previously, evidence specifically relevant to the magnocellular theory includes poor performance of dyslexics in the tactile domain (Grant *et. al.*, 1999; Stoodley *et. al.*, 2000), and the co-occurrence of the visual and auditory processing problems in certain dyslexics in sequential and temporal processing as

well as in automatic attention (Witton *et. al.*, 1998; Cestnick, 2001; Van Ingelghem *et. al.*, 2001, Facoetti *et. al.*, 2003).

Evidence of Pan-Sensory Processing Deficits in Dyslexia

Psychophysical Evidence

Impaired Sequential Processing of Rapid Stimuli

The existence of a general sequential processing deficit in children with dyslexia was demonstrated recently in a study testing the rapid sequential processing in dyslexic children in both the auditory and visual system using auditory gap detection and visual double flash detection (Van Ingelgheim, 2001). It was found that 70% of dyslexic readers had significantly higher thresholds than controls in both tasks. Furthermore, sequential processing measures were significantly related to word and pseudo-word reading skills.

Impaired Temporal Processing of Dynamic Stimuli

Dyslexic subjects have been found to be less sensitive than control subjects at detecting particular rates of frequency modulation and detecting visual coherent motion, and moreover, the sensitivity to dynamic stimuli in both modalities correlated highly. In addition, nonword reading, a measure of phonological awareness was also found to relate to these sensory measures (Witton *et. al.*, 1998).

Impaired Spatial Attention

A recent study measuring the covert automatic capture of both auditory and visual attention in dyslexics and normal readers revealed abnormalities in both modalities (Facoetti *et. al.*, 2003). Dyslexics showed impaired response to cued targets at short intervals, suggesting deficits in early automatic engaging of attention as well as longer response to cued targets at longer intervals, attributed to an impairment in the covert withdrawal of attention.

As discussed earlier, attention is said to select competing stimuli by a facilitation mechanism and inhibition mechanism, both working as integrated processes of spatial selection, hence these results suggest that children with dyslexia have defective spatial orienting and selection not just the visual but also the auditory modality. Moreover, these deficits correlated with phonological awareness deficits in the dyslexic children.

Anatomical Evidence

Anatomical evidence for a deficit that extends beyond the visual domain comes from magnocellular abnormalities in the medial as well as lateral geniculate nucleus of dyslexics' brains (Livingstone *et. al.*, 1991; Galaburda *et. al.*, 1994).

Problems with the Pan-Sensory Deficit Theory

The new magnocellular or pan-sensory deficit theory, unique in its ability to account for all manifestations of dyslexia, is undoubtedly attractive. Nevertheless, it also has its problems and has been facing growing criticism in recent years (Ramus, 2001). There is some negative evidence regarding cross modal sensory deficits (Heim *et. al.*, 2001). More generally, the idea that that the magno-/parvocellular distinction can be extended to non-visual sensory systems remains controversial.

Problems with the Visual Deficit Theory

The magnocellular theory is considered vulnerable, even if negative results are still scarce. Most of all, the attempt to correlate a psychophysical deficit in M-system visual functions with behavioural performance has not always been convincing. Moreover, recent studies reported more negative than positive evidence for the existence of a deficit in contrast sensitivity in dyslexia (Habib, 2000). Skottun pointed out unclear causal effect of magnocellular on the reading disability and the problem of extending or redefining the magnocellular system because it is also related to other areas that require more for reading (Skottun, 2000). He argued that deficits in movement perception should be conceptualised in terms of deficits in extrastriate cortical areas, which means the current theory is insufficient to explain the phenomena.

In general, one line of criticism of the visual magnocellular theory focuses on failures to replicate findings of a visual deficit (Victor *et. al.*, 1993; Johannes *et. al.*, 1996), on findings of such a deficit only in a sub group (Cornelissen *et. al.*, 1995; Witton *et. al.*, 1998; Amitay *et. al.*, 2002), and also on inconsistencies between predictions and empirical results. Another line of criticism focuses on the fact that visual impairments, when found, seem to be observed across a whole range of stimuli and not just those specifically tapping the magnocellular system (Skottun, 2000; Amitay *et. al.*, 2002; Farrag *et. al.*, 2002).

Problems with the Auditory Deficit Theory

Controversial issues on the temporal processing theory have been suggested (Habib, 2000). It was found that the poor performance of dyslexic children in the phonemic differentiating task could not be attributed to the temporal order difficulty, rather attributable to phonetic distance with using /da/-/sa/ and /ba/-/sha/ stimulus, which are phonetically more contrasting than /ba/-/da/ , although statistical power and subject selecting problems were argued in this case (Mody et. al.. 1995). McAnally also pointed out the weak causal link between temporal process and the reading disability with trying to improve identifying skill of dyslexic children using time-stretched synthetic consonant-vowel-consonant stimuli et. al.. (McAnally, 1997).

In general, criticism of the auditory theory emphasizes a number of failures to replicate findings of auditory disorders in dyslexia (Health et. al., 1999; Hill et. al., 1999; McArthur and Hogben, 2001), or the demonstrations of an auditory deficit only in a subgroup, ranging from a few isolated individuals to 50% of the population studied (Tallal, 1980; Reed 1989; Manis et. al., 1997; Mody et. al., 1997; Adlard and Hazan, 1998; Lorenzi et. al., 2000; Marshall et. al. 2001; Rosen and Manganari, 2001). Another line of criticism focuses on results that are inconsistent with the idea that the auditory deficit lies in 'rapid' auditory processing, and therefore with magnocellular function: indeed, with some tasks 'rapid' auditory processing is found to be intact, while with others 'slow' auditory processing is found to be impaired (Reed, 1989; McAnally and Stein, 1996; Adlard and Hazan, 1998; Schulte-Körne et. al., 1998b; Witton et. al.., 1998; Nittrouer, 1999; Lorenzi et. al., 2000; Rosen and Mangari, 2001; Share et. al., 2002). It is also argued that auditory deficits do not predict phonological deficits (Mody et. al., 1997; Schulte-Körne et. al., 1998a; Bishop et. al., 1999; Marshall et. al., 2001; Rosen and Manganari, 2001; Share et. al., 2002).

1.2.7 Cerebellar Deficit Theory

The third explanation of the cause of dyslexia, the cerebellar deficit theory, places the mechanism for reading disorders within the domain of learning as opposed to language or perception.

Information Processing and Learning Deficits

The cerebellar deficit theory has been proposed in light of evidence of learning deficits that are not just confined to the acquisition of phonological skill, but to general skill acquisition, both cognitive and motor. These are addressed in the 'automatization deficit' theory.

Also the theory attempts to explain deficits in information processing that are not just confined to perceptual processing, but general information processing, and, more specifically, the speed of information processing. It is interesting to note that the impediments in processing that are addressed in both theories share a common aspect in that they arise from fundamental speed impairments. However, as delineated earlier, the pans sensory deficit is based on impairments in the low level 'processing of speed' (specifically transient and rapid sequential stimuli). These impairments, on the other hand, arise from deficits in the overall 'speed of processing', particularly at higher attentive processing levels, and are addressed in the 'double deficit' theory.

Automatization Deficit Theory

This most recent theory predicts that the core deficit responsible for dyslexic problems is related to skill acquisition. In other words the phonological deficit is secondary to a more general learning deficit, which results in difficulties with the automatization of any new skill (Nicolson and Fawcett, 1990; Nicolson et. al., 2001).

Background to the Automatization Deficit Theory

An interest in a general learning-related explanation for dyslexia began in the 1990s when Rod Nicolson and Angela Fawcett conducted a longitudinal study of 23 dyslexic children and found a wide spectrum of symptoms that could not be accounted for by the phonological theory. They observed that although the disability suffered by dyslexic children was indeed one of learning, it was by no means specific to learning to read, rather, it was a deficit in learning any cognitive and motor skill and was confined to the final stage of skill acquisition, known as 'skill automatization'.

Indeed, the concept of automaticity is crucial in reading. Laboratory research indicates that the most critical factor beneath fluent word reading is the ability to recognise letters and whole words effortlessly and automatically and the central goal of all reading instruction depends crucially on this ability (Adams, 1990). There is also evidence that, even when dyslexic children have managed to acquire reasonably good literacy skills, their reading is slower, more effortful and less automatic than normal readers of the same reading age (Nicolson and Fawcett, 2001).

Evidence of Automatization Deficits in Dyslexia

In 1990, Nicolson and Fawcett formulated the 'automatization deficit' theory, that dyslexic children have unusual difficulty in making skills automatic, despite extensive practice, regardless of whether the skill is cognitive or motor. 'Conscious Compensation' hypothesis, that dyslexic children are normally able to overcome their automatization deficit by means of conscious compensation that is, by trying harder and/or by using strategies to minimize or mask the deficit (Nicolson and Fawcett, 1990).

One reason why dyslexia theorists had not seriously considered learning as a viable framework for dyslexia is that it fails to account for the apparent specificity of the deficits in dyslexia. A general problem in learning would result in a problem in all learned skills, cognitive and motor. However, careful observation of dyslexic children suggests that although they appear to be behaving normally, they show unusual lapses in concentration or appear to tire more quickly when performing a skill.

In order to explain this seeming discrepancy, Nicolson and Fawcett coined a parallel theory, the 'conscious compensation' theory, namely that, despite their more limited automaticity of skill, dyslexic children are able to perform at apparently normal levels most of the time by consciously compensating, that is by trying harder and/ or by using strategies to minimize of mask the deficit (Nicolson and Fawcett, 1990). This leads to apparently near normal performance at the expense of speed and effort. Problems remain apparent in skills requiring rapid performance or fluent interplay of a range of subskills (Fawcett and Nicolson, 1995).

In other words dyslexics use 'controlled processing' on performance that might normally be 'automatic processing'.

Behavioural Evidence: Motor Skill Deficits

Impaired Non Linguistic Motor Skills

The automatization deficit theory predicts that there will be deficits not only in articulation skill but also in simple motor skills with no linguistic component, whereas the phonological deficit suggests that although there may well be an articulatory skill deficit, any other impairment will be relatively mild and transient (Nicolson and Fawcett, 1995). Fine and gross motor skills have absolutely no linguistic component, so any deficits found would be hard to explain in terms of a specific deficit in phonological skill and could only be explained in terms of a problem in general skill automatization. Therefore the area of motor skills provides the opportunity for

distinguishing between an automatization deficit and phonological deficit account for the impairments suffered by dyslexic children.

In the 1980s considerable evidence was provided for a deficit in motor skills in dyslexic children. Impairments were observed in several motor skills, including speed of tapping, heel-toe placement, rapid successive finger opposition and accuracy in copying (Denckla, 1985). Based upon these observations, Martha Denckla suggested that children with dyslexia are characterized by a non-specific developmental awkwardness, so that even those children with dyslexia who show reasonable athletic ability are poorly coordinated. Since this awkwardness is typically outgrown by puberty, this pointed to a possible maturational lag in the motor analyser that programs timed sequential movements (Rudel, 1985). Moreover, these deficits appeared to be primarily in the acquisition of new tasks, which is typically awkward and effortful, but once the skill is successfully acquired or learnt, dyslexic performance is essentially normal (Denckla, 1985).

Another comprehensive study summarized a good deal of clinical evidence, deriving 21 classic problems for dyslexic children (Augur, 1985). The majority of them were related to reading and phonological skills, but a surprisingly large number, including clumsiness, difficulties in hopping and skipping, clapping in rhythm and throwing and catching a ball, indicated problems in motor skill. A subsequent longitudinal study, the British Births Study, examined aspects of health in a cohort of 1,700 children born in 1970, at birth, 5 and 10 years (Haslam, 1989). One of the purposes of the study was to identify predictors of dyslexia in children by investigating those characteristics that correlated highly with the established symptoms of dyslexia at age ten. Two motor skills were among the six variables that were emerged as significantly different between dyslexic and normally achieving children at age 10: dyslexic children were unable to throw a ball up, clap and catch it again and unable to walk backward in a straight line for six steps.

In 1990, based on these previous findings, Nicolson and Fawcett carried out the first basic study to test both automatization and conscious compensation in dyslexic children, which, in fact, led to the proposal of the automatization deficit and conscious compensation theories (Nicolson and Fawcett, 1990). Using the task of balance, selected because it is a highly practiced motor skill with no phonological or reading component, they found that dyslexic children were able to balance normally under 'just balancing' conditions but, unlike normal children, their performance deteriorated significantly when they were asked to perform another task concurrently, such as counting backwards or pressing a button for a tone (Nicolson and Fawcett, 1990). In order to ascertain whether this impairment was attributable to the prevention of conscious compensation or some other attentional problems associated with the performance of

two simultaneous tasks, the subjects were also blindfolded in a further study, thereby preventing conscious compensation without introducing the complications of a dual task design, and the dyslexics continued to be impaired (Nicolson and Fawcett, 1992). This suggests that, unlike the controls, the dyslexic children need to invest significant conscious resources for monitoring balance, and thus their performance is adversely affected by any concurrent secondary task that serves to distract attention from the primary task.

On the basis of this argument it follows that the ability to hear the constituent phonemes in a word, that is, phonological awareness, is a learned skill that normal children master to the extent that it is automatic, whereas dyslexic children may well not achieve such levels of automaticity.

Impaired Linguistic Motor Skills

There is also considerable evidence that children with dyslexia are impaired in articulatory motor skills (Snowling, 1981), but it is not clearly established whether this is based predominantly on a phonological deficit or a motor skill deficit in the rate or accuracy or articulation. However, poor readers, up to age 10, showed deficits in their speed of repetition of simple couplets, which led to an argument for a developmental lag in motor timing control. Adolescents with dyslexia have also demonstrated problems in rapid paced repetition of sequences (Wolf et. al., 1984). When required to repeat the sequence 'pa-ta-ka', entrained to the beat of a metronome, dyslexics had difficulty in constructing a fluent speech rhythm, particularly at faster speeds (Wolff et. al., 1990). Similar deficits have been found for this age group in repetition of simple and complex phrases (Catts, 1989). Moreover, although 8 year old children with dyslexia were found to be significantly slower and less accurate in repeating polysyllables and nonsense words, they found no impairment in accuracy of speed of a single repetition of high- frequency monosyllables, suggesting that children are slower and more error prone on complex articulation tasks, but their performance appears to be normal on simple, familiar words (Brady et. al., 1989).

In a study testing both linguistic and non-linguistic primitive motor skills in dyslexics, the performance of dyslexic children has been found to be inferior to that of their chronological age matched controls on articulation rate, peg board and bead threading (Fawcett and Nicolson, 1995). Moreover, although their speed of articulation and speed of moving pegs were equivalent to their reading age controls, their performance in bead threading was significantly worse than even their reading age controls.

Behavioural Evidence: Cognitive Skill Deficits

In addition to motor skill deficits, the comprehensive study by Augur in 1985 revealed another set of deficits, including difficulty in carrying out several instructions simultaneously, high distractibility and rapid tiring under continuous load (Augur, 1985). These deficits were consistent with problems in fluency for cognitive skills, specifically with central attentional problems. Since then a number of other studies have found substantial differences in cognitive skills, particularly in the speed of processing.

As discussed previously, a key idea in cognitive neuroscience is that differences in mental ability are related to speed of mental processing. To test this notion, a number of investigators have sought to correlate reaction time in dyslexics with cognitive test performance.

Recently extensive evidence has emerged for difficulties in the speed of processing for a variety of reaction time tasks. This is distinct from the evidence of a sensory and perceptual deficit in the 'processing of speed', which has already been addressed in an earlier section, where the distinction between the two terms was also made. The evidence here comprises tasks wherein a delay in speed of sensory or perceptual processing is unlikely to be involved, and the delays are most likely due to higher cognitive or 'central' processing.

Impaired Speed of Processing in Linguistic Tasks

Naming speed deficits are the deficits in the processes underlying rapid recognition and retrieval of visually presented linguistic stimuli. There is extensive evidence that many severely impaired readers do indeed have naming speed deficits (Wolf and Bowers, 1999), particularly in the 'rapid automatized naming' test developed by Denckla and Rudel in 1972. This test involves the rapid naming of a visual array of fifty stimuli, consisting of five symbols in a given category (letters, numbers, colours or objects) that are presented ten times in random order (Denckla and Rudel, 1976).

A 5-year longitudinal study has established that early deficits in naming and speed for letters and numbers predicted later deficits in reading, with a direct relationship between the speed deficit and the severity of the reading impairment (Wolf, 1991).

These findings have been extended to non-linguistic stimuli, in a series of naming speed tests with several groups of children with dyslexia and mild reading difficulties (slow learners) (Fawcett and Nicolson, 1994). The tests have revealed that children with dyslexia, as well as slow learners, are significantly slower than chronological age matched controls, and equivalent to their reading age controls, on naming colours, digits and letters, and significantly slower than even their reading age controls on naming pictures of common objects (Fawcett and Nicolson,

1994). This suggests that dyslexic children have persistent and unexpectedly severe problems in naming speed for all stimuli, regardless of whether or not the stimulus requires grapheme-phoneme decoding. That is, dyslexics may have impaired speed of access to their lexicon for all types of stimuli regardless of the mode of presentation. Moreover, the differences in results for picture naming versus colour, digit and letter naming led to the proposal that dyslexic children do not have a fundamental deficit in speed of reaction, but that their deficit increases as the number of possible responses increases, in line with the amount of processing required (Fawcett and Nicolson, 1994).

Double Deficit Hypothesis

Based on this underlying theme of a specific impairment in task fluency, Maryanne Wolf and Patricia Bowers have proposed an alternative conceptualisation of developmental dyslexia, the 'double deficit hypothesis', which suggests that the processes underlying phonological deficits and naming-speed deficits represent two separable sources of reading dysfunction and the combined presence of both these leads to profound reading impairment (Wolf and Bowers, 1999).

Hence Wolf and Bowers argue that dyslexic children suffer from two crucial 'core deficits': phonological processing problems and rapid processing problems, and provide strong evidence that if a child suffers from both problems as indicated by difficulties on segmentation (phonology) and rapid naming (speed), his/her educational outlook is significantly worse than a child suffering from only one deficit (Wolf & Bowers, 1997).

Although there is little disagreement concerning the behavioural evidence of naming speed in dyslexic readers, there are substantive differences regarding how these deficits should be categorized. Current practice amongst most reading researchers is to subsume naming speed under phonological processes as, for instance, the retrieval or phonological codes from a long-term store. However, some researchers are inclined to view phonological processing and naming speed as separate specific sources of disability and argue that naming speed deficits should be categorized as 'central' processing speed deficits, and thus considered separate from phonological-based deficits for theoretical and applied reasons (Wagner *et. al.*, 1994).

In other words, in contrast with the phonological processing problems, the rapid processing problems arise from a general deficit in the speed of information processing, regardless of the linguistic basis of the task.

It is clear that one of the striking features of the performance profile for dyslexic children that there is indeed an impairment in speed in almost any skill. Anecdotal reports suggest this lack of fluency may characterize dyslexic performance across a range of skills (Miles, 1983). This impairment may be clearly seen in analysis of scores on the Wechsler Intelligence Scale for Children (WISC) tests widely used in the diagnosis of dyslexia (Wechsler, 1992). The performance of dyslexic children on the individual components typically shows an abnormally spiky profile, reflecting a distinctive pattern of strengths and weaknesses, with impairments in Arithmetic, Coding, Information and Digit Span (Newton, Thomas and Richards, 1976). Digit span and coding are both linked to speed of processing. It is recognised that, in addition to phonological effects, developmental improvements in digit span co-vary with those in processing speed possibly via the mechanism of articulation (Nicolson, 1981, Hulme *et. al..* 1984). Furthermore, there is evidence that the reduced memory span of children with dyslexia is accompanied by an equivalent slowness of articulation rate (Nicolson, Fawcett and Baddelly, 1991). The coding subtest requires the user to cross out examples of a particular (non alphabetic) symbol in a list of such symbols. It clearly implicates speed of processing and indeed coding is a major component of the WISC-II 'speed of processing' index.

It is interesting to note that a recent study examined the relationship of attention deficit hyperactivity disorder (ADHD) and reading disabilities to balancing problems and rapid processing problems and found that poor balancing, assessed both singly and together with a secondary task, was not found to be associated with the children with reading disability, but with ADHD (Raberger and Wimmer, 2003). In contrast, poor performance on the rapid naming tasks, both digit and colour naming, was found to be associated with reading disability and not ADHD.

Impaired Automatic Cognitive Skill in Attentional Tasks

Previous studies have provided evidence for attentional deficits in visual spatial attention. Results have shown that dyslexics have a specific difficulty in attention focus and attention orientation. In attention orienting tasks, dyslexics have trouble in attention shifting caused by peripheral cues that are used to elicit automatic orienting of attention, and are also able to maintain 'attention focus' for short periods of time only, but have no disability in attention shifting caused by central cues that are used to elicit voluntary covert orientation of attention. Such results may also support the suggestion that visual selective attention deficits in disabled readers may be due to a specific difficulty in automatic attention orienting and subsequent attention focusing. It is therefore possible that the processing speed of stimuli in dyslexics is normal once attention has been allocated to them, but that this allocation takes longer than usual.

One study examined the nature of the attentional disorders in non-spatial contexts in dyslexia by measuring the sustained attention of dyslexic children in tasks that require the withholding of responses to rare targets (Moores and Andraide, 1998). It was found that dyslexics were impaired in the automatic recognition of stimuli, rather than sustained attention.

Another more recent study investigated these automatisation abilities of dyslexics in attention further by separately studying each of the three components of attention: focusing, switching and sustaining (Moores et. al., 2003). It found that although dyslexics were unimpaired in their ability to focus and sustain attention, they demonstrated a clear deficit in the condition where they had to switch attention between two target types. Interestingly the time course suggested that the problem was not caused by difficulties in switching attention rapidly but in maintaining the rapid responses several seconds after switching. In other words, the attention switching mechanisms appeared to be working normally in dyslexia, but they were adversely affected by continual target switches, thereby suggesting a problem with central attention, per se as opposed to any particular component of attention. Attention switching can be considered a dual task, requiring all the skills necessary for attention focus as well as the switching and maintenance of the current target in memory. Thus if some component of the basic focus task is not automatized in dyslexics, such as automatic shape recognition and/ or automatic response, the available resources required to perform the extra components of the shift condition are likely to be scarce.

The cause of this deficit was explored further by using visually degraded stimuli, which require more attentional capacity to process than normal visibility stimuli and therefore use more attentional resources and prevent the automatic shape recognition. The visual degradation of was found to impair the performance of the controls but not the dyslexics, suggesting that the dyslexics were performing the shape recognition task non automatically even with intact stimuli, whereas the controls changed from automatic to controlled processing, which is slower and limited by attentional resources. In other words the dyslexic impairment was, indeed, due to a general deficit in automatic performance, as opposed to reduced attentional resources.

Electrophysiological Evidence

Event related potentials offer the means to directly identify whether the slowed speed of processing that has been observed in dyslexics is attributable entirely to stimulus categorization problems, or whether there is some response selection, since the two components of cognition are difficult to distinguish using behavioural reaction time methods. In a study by Fawcett and Nicolson, dyslexic children showed a deficit in the latency of the P3 wave during a selective

choice reaction task to auditory tones (Nicolson and Fawcett, 1993). Furthermore, the latencies correlated highly with selective choice reaction latencies obtained in their previous study (Nicolson and Fawcett, 1994). Since the latency of the P300 wave is thought to provide an index of stimulus classification speed uncontaminated by response selection factors, this finding provided strong evidence that the deficit in speed of mental processing in dyslexic children is not attributable to motor response selection or execution, and appears to be linked to the need to make a discrimination between stimuli.

Hence the automatization theory suggests that the dyslexic deficit in speed of processing is caused by bottlenecks, which arise at many stages in central processing, as opposed to sensory processing or response preparation. Moreover, the difficulties appear to be exacerbated by task difficulty. Nonetheless, the bottlenecks arise even in fundamental processing speed and in the absence of significant memory load or verbal material. By contrast the dyslexics show no evidence of any difficulties in sensory processing speed, though it is quite possible that sensory/ perceptual difficulties are impaired. The theory suggests that there is some inefficiency in the 'central executive' processing system.

It is important to point out, at this stage, that the automatization theory is best seen as a theory at the descriptive level, because although it provides an extensive account of the symptoms, it does not address the neurological underpin of dyslexia.

Thus, in addition to difficulties in their ability to discriminate between different sensory stimuli if they are presented nearly simultaneously, dyslexics have difficulties in generating active responses that require rapid succession (Llinas, 1993). This includes speed deficits in lexical tasks, in visual tasks and auditory tasks. It is important to note that a common element in all these theories is the certainty that timing or speed skills, specifically rapid timing skills, are a fundamental problem area in dyslexia, in sensory, cognitive and motor tasks. In other words, speed deficits underlie visual and auditory perception problems, as well as cognitive and motor fluency problems, and even motor coordination problems, all of which have been proposed as adversely affecting the development of language skills.

Neurological Evidence

In the 1990s it was noted that most of the deficits in motor skill and automatization in dyslexics described above appeared to be similar to those observed in cerebellar patients. Moreover, the cerebellum has also been implicated in dyslexia by virtue of its rich anatomical connections with the magnocellular system, which is believed to be a fundamental culprit in dyslexia. This

drew attention to the cerebellum as a possible neurological substrate for some or all of the difficulties observed in dyslexia.

Thus the 'cognitive level' automatization theory was subsequently subsumed into a 'neurological level' theory, that is now known as the 'cerebellar deficit theory'.

Background to the Cerebellar Deficit Theory

The Cerebellum

The cerebellum is a densely packed and deeply folded subcortical brain structure at the posterior of the brain, made up of two cerebellar hemispheres. In humans it accounts for about 10%-15% brain weight, 40% of brain surface area and 50% of the brain's neurones. Long seen as an important regulator of reflex and voluntary movements, the cerebellum is now recognised as critically important in may aspects of sensorimotor control and learning. Damage to different parts of the cerebellum can lead to different symptoms in humans, ranging from disturbances in posture and balance, to limb rigidity, loss of muscle tone, lack of coordination and impaired timing of rapid pre-planned, automatic movements (Fawcett and Nicolson, 2000). However, one of the key features of the cerebellar system is its plasticity, which means that near normal performance can be regained within a few months of damage (Holmes, 1992).

Cerebellum and Motor Skills

The cerebellum has traditionally been considered a motor area (Stein and Glickstein, 1992). In particular, there is extensive evidence that the cerebellum is centrally involved in the acquisition of motor skill by way of its rich connections to the motor cortex, to the skeleto-muscular system, and to sensory cortex (Marr 1969, Albus, 1971, Ito, 1984). One influential model of its role proposes that following a motor movement, the cerebellum receives signals that indicate a mismatch between plan and execution by way of the climbing fibres from the inferior olive, and these error signals allow the cerebellum to tune the motor plan timing and execution. A cerebellar inactivation study in rabbits has provided direct evidence that the cerebellum is centrally involved initial skill acquisition. A clear role of the cerebellum in human motor skill acquisition was provided by a recent PET study that revealed that cerebellar activation associated both with new learning and with automatic sequential movement, but most extensively in new learning (Jenkins et. al., 1994). It proposed that the cerebellum is involved in the process by which motor tasks become automatic (Fawcett, Nicolson and Dean, 1996).

Cerebellum and Cognitive Skills

The concept that the cerebellum is involved in cognitive skills has lad to considerable controversy, because the cerebellum has traditionally been seen as a motor learning area, involved in learning and the automatization of motor skill, motor control and coordination.

However, recent research of cerebellar patients has led to a reappraisal of the role of the cerebellum and extended the contribution of this motor analyser of the brain to cognitive functions. Neuroimaging studies have found that the cerebellum is activated in cognitive activities including mental imagery (Ryding et. al., 1993), word processing and working memory, even without overt speech. Furthermore, neuropsychological studies of patients with cerebellar damage have identified deficits in cognitive skills including rapid attention shifting between modalities (Akshoomoff and Courchesne, 1992), non motor learning and error detection (Fiez et. al., 1992) and judging time intervals (Ivry and Keele, 1989). Other cognitive functions involving the cerebellum include abstract reasoning, emotion and the ability to process logical sequences (Vicari et. al., 2003). One study has demonstrated a specific impairment in the procedural learning of adults with cerebellar lesions, suggesting a cerebellar role in detecting and recognising event sequences and in acquiring and automatizing new cognitive procedures (Molinari et. al., 1997). It is interesting to note that precisely these capabilities appear to play a decisive role in reading, which requires the acquisition and automation of several competencies, such as the processing of eye movements, elementary articulatory skills and letter recognition.

Indeed, the involvement of the cerebellum in cognition is one of the most topical and dynamic areas of cognitive neuroscience research, with a plethora of potential roles now posited, including timing, attentional shifting, sensory acquisition and discrimination (Fawcett, Nicolson and Dean, 1996). Yet, it has still been discounted as a causal factor in dyslexia owing to its supposed lack of involvement in language.

Recent evidence, however, suggests that the cerebellum may indeed be involved significantly in language development (Gebhart, Peterson and Thach 2002). The human cerebellum has evolved tremendously having become linked not only with the frontal motor areas, but also more rostral areas in the frontal cortex, including Broca's language area, making it critical in the acquisition of language dexterity (Leiner, 1993). It is also suggested that the cerebellum may help to mediate the inner speech that is required for phonological analysis, that is, mentally sounding out the letters in a word. There is now increasing evidence of the importance of the cerebellum in language, including specific cerebellar involvement in reading. In effect, it has

been proposed that the cerebellum is critically involved in the automatization of any skill, whether motor or cognitive.

Evidence of Cerebellar Deficits in Dyslexia

Behavioural Evidence

Clinical Symptoms

If there is indeed cerebellar impairment in dyslexics, they should also show traditional signs of cerebellar dysfunction (Nicolson, Fawcett and Dean, 1995). Although there has been no conclusive evidence of impairments on the two main cerebellar motor symptoms of dystonia (problems with muscle tone) and ataxia (disturbances in posture, gait or limb movements), a recent study by Fawcett, Nicolson and Dean has shown impairments on a range of other similar cerebellar motor tasks (Fawcett, Nicolson and Dean, 1996). This study was conducted with the same groups of children as the time estimation study described previously. The dyslexic and control children in three different age groups of 10, 14, and 18 years were compared on a total of 14 tasks that fell into three categories: posture and muscle tone, hypotonia of upper limbs and complex voluntary movement. Analysis showed that the performance of the dyslexic children was worse than chronological age controls on all 14 tasks, and worse than reading age controls on 11 out of the 14 tests. The results were then normalized for each test for each group relative to the corresponding control group to produce an age appropriate 'effect size' in standard deviation units so that children were deemed at risk if their performance fell one standard deviation below that expected for their age. It was found that all but one task produced an overall effect size for the dyslexic groups of minus one or worse.

This research was extended a few years later with a further sample of 126 children in four age groups, in which the dyslexics and controls were administered both a range of cerebellar tasks and other tasks sensitive to dyslexia. In all the cerebellar tests and phonological awareness tests, dyslexic children performed significantly worse than controls. Moreover, the pattern of difficulties was in line with the earlier study, with the poorest performances on postural stability and muscle tone, comparable in magnitude to the deficits in reading and spelling, and greater than the deficits in segmentation and non-word repetition.

These tests provided clear behavioural evidence of cerebellar abnormalities, at least in the selected groups of dyslexics.

In any deficit, behavioural data provides strong but, nonetheless, indirect evidence of any impairment in the implicated brain region, hence an important requirement is to assess the anatomy and function of the region directly where possible. This would also enable a more clear indication as to the locus of abnormalities in the region.

Impaired Time Estimation

Although the traditional symptoms of cerebellar dysfunction are motor signs such as dysmetria and incoordination, behavioural studies have also uncovered problems in chronometric tests. In a test involving temporal judgement it was found that cerebellar patients were particularly impaired on both production and perception of timing tasks, but, by contrast, showed no impairment on a loudness judgement task that was intended as a non-cerebellar control task (Ivry and Keele, 1989).

This study was replicated with dyslexic children, who showed a severe deficit on time estimation compared to the controls, but not on loudness estimation (Nicolson *et. al., 1995*). Given that temporal estimation makes no demands upon phonological processing, speeded processing or motor skill, most of the extant theories of dyslexia would predict no impairment, and this result strongly suggests a deficit in cerebellar function. Dyslexics have also been shown to have problems in complex tapping tasks (Wolff *et. al.*, 1990).

One theory in dyslexia, which night predict a similar pattern of results, is a recent proposal by Llinas that the deficits in dyslexia might be traced back to dyschronia or general timing deficit in a thalamocortical circuitry (Llinas, 1993). However this would predict difficulties only in rapid sequential processing rather than in temporal estimation.

Impaired Eye Blink Conditioning

The cerebellum is considered to be the major structure involved in motor learning, and in the classical conditioning of motor responses in particular (Yeo *et. al.*, 2000). The most frequently used experimental procedure for classical conditioning is eyeblink conditioning. This involves the presentation of a behaviourally neutral conditioned stimulus (CS), such as an auditory tone or light flash, followed after a fixed time interval by an unconditioned stimulus (US), such as an air puff to the cornea of the eye. The US always elicits a reflexive eye blink, which constitutes an unconditioned response (UR), whereas the neutral CS does not elicit such a response when presented alone. However, after a sufficient number of paired CS-US presentations, wherein the subjects learn the association between the two stimuli, the condition response (CR) of an eyeblink occurs to the CS even before or without the onset of the US. The essential neuronal

circuitry underlying eyeblink conditioning is thought to involve the convergence of CS and US information in the cerebellum.

In this direct test of cerebellar function in learning, 13 dyslexics and 13 controls undertook an eyeblink conditioning experiment, with a corneal air puff as the US and an auditory tone as CS (Nicolson *et. al.*, 2002). During acquisition the CS and US were paired in 70% trials and the CS was presented alone in 30% trials, then during extinction the CS was presented alone in 100% of trials. Individual analyses indicated that 85% of the dyslexic group showed either no conditioning or abnormally poor CR tuning and/or abnormally low OR habituation. This demonstrates a fundamental abnormality in associative learning in dyslexics.

Impaired Implicit Learning

Implicit learning is thought to be a cognitive function primarily processed by the cerebellum. One study has tested both implicit and explicit learning in dyslexic adolescents, by employing a serial reaction time task to analyse prevalently implicit learning and then employing a serial reaction time task to analyse previously memorised declarative knowledge. Dyslexics showed a reduced learning rate in the implicit but not declarative task, suggesting a specific deficit of implicit learning and consequently providing further evidence for a cerebellar dysfunction in dyslexia (Vicari *et. al.*, 2003).

Physiological Evidence

Magnetic Resonance Spectroscopy

One study using Magnetic Resonance Spectroscopy (MRS) has revealed significant metabolic abnormalities in the cerebellum of dyslexics (Rae *et. al.*, 1998). The ratio of choline containing compounds to N-acetylaspartate, measured by MRS, gives an estimate of the metabolic activity of different brain regions. This ratio was found to be lower in the right cerebellum of dyslexics as well as their left temporo-parietal lobe (with which the right cerebellum connects). Moreover, the dyslexic cerebella showed lateralization differences, which were absent in controls.

Positron Emission Topography

A subsequent functional imaging study using PET has provided physiological evidence of cerebellar involvement in dyslexia (Nicolson *et. al.*, 1999). Brain activation was monitored in six dyslexics and six controls as they performed a prelearned sequence or learned a novel

sequence of finger movements. This motor sequence learning task is known to induce strong cerebellar activation, and allows the investigation of automatic prelearned performance as well as knew sequence learning that is completely unrelated to reading (Jenkins et. al., 1994). The blood flow analysis revealed that the control group showed relatively greater activation in the right cerebellum, compared with the 'at rest' state, both during performance of the prelearned sequence and in learning the new sequence. In contrast, the dyslexic group showed greater activation in large areas of the frontal lobe, compared with the 'at rest' state, when learning the novel sequence. Thus the dyslexic group showed significantly less cerebellar activation (only 10% compared with controls) when performing both the prelearned and novel sequences.

Recently, two additional brain-imaging studies have also shown activation differences in the cerebella of dyslexics (Brown et. al., 2001; Leonard et. al., 2001).

Anatomical Evidence

Post Mortem Analysis

Analysis of the post mortem tissue derived from the Orton Dyslexia society brain bank has revealed a fascinating range of differences between dyslexic and control brains. As described previously, early work indicated a decreased asymmetry of planum temporale, together with ectopias (brain warts) largely in the language ares of the left hemisphere, but also bilaterally and in non-language areas (Galaburda et. al., 1985). Subsequently, smaller magnocells were identified in visual pathways, and in the equivalent auditory pathways (Galaburda, et. al., 1994).

Most recently, an analysis of the cerebella of the same brain specimens measured the cross sectional areas and cell packing densities of Purkinje cells in the cerebellar cortex, inferior olive and dentate nuclei (Finch et. al., 2002). Dyslexics were found to have a significantly larger mean cell area in the medial posterior cerebellar cortex. Moreover an analysis of cell size distributions confirmed these differences, showing an increased proportion of larger neurons and fewer small neurons, and also revealed similar distribution differences in the anterior lobe and inferior olive. Thus anatomical evidence suggests a problem in the input to the cerebellum, rather than the cerebellar output to the dentate nucleus.

Structural Magnetic Resonance Imaging

Structural MRI studies of dyslexic adolescent adults have demonstrated differences from controls in a variety of brain regions, including the inferior frontal gyrus, insula, caudate, corpus collosum, left temporal lobe, thalamus and cerebellum (Pennington et. al., 1999; Eliez et. al.,

2000; Brown et. al., 2001; Leonard et. al., 2001; Rae et. al., 2002, Eckert et. al., 2003). The cerebellar and inferior frontal gyrus findings have been the most consistent.

Such widespread neuroanatomical differences between adult dyslexic and control brains led to a multivariate analysis approach to characterizing the dyslexic brain. One study used such an analysis in a volumetric MRI scan study examining the morphology of language related areas in a group of dyslexic students with reading disability (Leonard et. al., 2001). It was found that the phonological skills were predicted by four anatomical measures, one of which was a left asymmetry of the anterior cerebellar lobe. By contrast, oral and written comprehension skills were predicted by a different anatomical variable: low cerebral volume

Subsequently another neuroanatomical study in a group of dyslexic children has extended recent neuroanatomical findings by attempting to determine the probability of a dyslexia diagnosis for each of the anatomical measures, as well as to examine the relations between anatomical measures and measures of reading, spelling, and selected language skills related to reading (Eckert et. al., 2003). Measurements of the posterior temporal lobe, inferior frontal gyrus, cerebellum and whole brain were collected from MRI scans of 18 dyslexics and 32 controls. The dyslexics exhibited significantly smaller right anterior lobes of the cerebellum and pars triangularis bilaterally and brain volume. These measures correctly classified 72% of the dyslexic subjects, 94% of whom had a rapid automatic naming deficit. Moreover, the volume of the right anterior lobe of the cerebellum distinguished dyslexic from control participants in both studies. The right cerebellar anterior lobe was also the only anatomical measure that was comparable in the child dyslexics of this study, and the adult dyslexics of Leonard's study.

This effect may have been due to decreased grey matter rather than white matter. One study has reported that dyslexic adults failed to exhibit rightward whole cerebellum grey matter asymmetry, in part as a result of reduced volume of right cerebellar grey matter, while there was no difference between control and dyslexic subjects for whole cerebellum white matter measures (Rae et. al., 2002).

Thus the cerebellum has emerged as one of the most consistent locations for structural differences between dyslexic and control participants in imaging studies and there is now very little doubt that cerebellar function is mildly disturbed in many dyslexics.

Linking Cerebellar and Reading Deficits in Dyslexia

Children with cerebellar tumours often present with reading difficulties (Scott et. al., 2001). The left temporo-parietal area projects to the right cerebellum, and both these regions are particularly involved in language related processes. Moreover, children with right-sided cerebellar lesions tended to have language and literacy problems while those with left sided lesions were more likely to have visuospatial problems (Scott et. al., 2001). In fact, these cerebellar tumours seem to cause more serious and long lasting problems than lesions of the cerebellar cortex, whereas if cortical lesions occur early enough, most children recover from them almost completely.

The proponents of the cerebellar deficit theory have proposed a causal chain linking cerebellar problems and eventual problems with reading as well as spelling and writing. Moreover, the difficulties are accounted for by routes through phonological processing as well as binocular control, and by direct and indirect routes to reading. This indicates that these difficulties might derive from a number of inter-dependent factors.

Cerebellum and Phonological Processing in Reading

First, since the cerebellum plays a role in motor control and therefore speech articulation, it is postulated that retarded or dysfunctional articulation would lead to deficient phonological representations. Secondly given that the cerebellum plays a role in the automatization of over learned tasks, a weak capacity to automatize would affect, among other things, the learning of grapheme-phoneme correspondences. Thirdly, the cerebellum may also help to mediate the inner speech, thus any difficulties with mentally sounding out the letters in a word would further affect phonological analysis. These are the direct routes from cerebellar abnormality to reading difficulties, through phonological processing.

Dysfunctional articulation also affects reading through two indirect routes. If articulation is less fluent than normal, then one indirect effect is that it takes up more conscious resources, leaving fewer resources to process the ensuing sensory feedback necessary for reading. A second indirect effect is that reduced articulation speed leads to a reduced effective working memory, as reflected in the phonological loop, which in turn leads in difficulty in language acquisition.

Cerebellum and Visuomotor Control in Reading

The cerebellum is known to be important for the acquisition of all sensorimotor skills. Its particular contribution to reading is its involvement in the control of eye movements: fixation, saccades, smooth pursuit, and vergence. It plays an important part in calibrating the visual motion signals to help maintain steady binocular fixation (Miall, Wolpert and Stein, 1993). It

also calibrates reading eye movements to be precisely adjusted for each short saccade from one word to the next, and also to control those long saccades that take the eyes back to the beginning of each line (Stein, 2001).

Thus cerebellar problems in dyslexics may lead to the unsteady control of eye movements involved in reading. Indeed, the eye movements of dyslexics have been found to be similar to those of patients with cerebellar lesions (Stein 2001).

Cerebellum and Deficits in Writing and Spelling

Cerebellar deficit provides a natural, direct explanation of the execrable quality of writing frequently shown by dyslexic children, since handwriting is a motor skill that requires precise timing and coordination of diverse muscle groups. For spelling, problems arise from several indirect routes: over effort in reading, poor phonological awareness and difficulties in automatizing skills (Nicolson, Fawcett and Dean, 2001).

A cerebellar deficit would therefore be predicted to cause, by direct and indirect means, the phonological deficits observed in dyslexia.

Problems with the Cerebellar Deficit Theory

The main problem of the cerebellar theory is that it fails to account for perceptual disorders, though its proponents do support the idea of distinct cerebellar and magnocellular dyslexia subtypes. Another drawback for the theory is that it is uncertain what proportions of dyslexics are affected by 'cerebellar' motor problems. A number of studies have failed to find any such deficits, (Wimmer *et. al.*, 1998; van Daal and van der Leij, 1999; Kronbichler *et. al.*, 2002), while others have found motor deficits only in a subgroup of dyslexics (Yap and van der Leij, 1994; Ramus *et. al.*, 2003), and it has often been suggested that motor dysfunction is found only in dyslexic children who also have attention-deficit hyperactivity disorder (ADHD) (Denckla *et. al.*, 1985; Wimmer *et. al.*, 1999).

1.2.8 The Three Theories of Dyslexia: Causes, Correlations or Consequences?

Before embarking on a description of the four studies carried out in this project and a discussion of the results obtained, it is valuable to consider how the three alternative theoretical formulations for dyslexia relate to each other.

It must be noted at the outset that there is a qualitative difference between the various theories that have been discussed: the magnocellular deficit and cerebellar deficit theories are both based upon an underlying neural substrate and, thus, both have 'biological level' descriptions. Conversely, the phonological deficit theory, as well as the automatisation deficit theory and double deficit theory are based largely upon non-biological theoretical mechanisms and, thus, have 'cognitive level' descriptions.

All Inclusive Magnocellular Deficit Theory

John Stein, the proponent of the magnocellular theory has argued that cerebellar impairment might be attributable to faulty input via impaired magnocellular pathways (Stein, 1999?). It seems clear that there is a subtype of dyslexia with magnocellular impairment and, possibly, a pan-sensory impairment, including motor output as well as visual and auditory input. Stein refers to the cerebellum as "the brain's autopilot, specialized for automatic pre-programmed timing of muscle contractions for optimising motor performance" (Stein, 2001). Accordingly, it requires and receives rich magnocellular projections from all sensory and motor areas. Indeed, the cerebellum is the largest output of the dorsal magnocellular route, via the pontine nuclei (Stein, 1986; Stein and Glickstein, 1992). Likewise, the dorsal spinocerebellar tract is dominated by dynamic signals provided by Group IA muscle spindle fibres. Furthermore, the Purkinje cells of the cerebellum demonstrate some of the heaviest staining with the magnocellular marker, CAT 301. Thus the cerebellum not only receives timing signals from the magnocellular system, but it also can be considered itself, the most important part of the magnocellular timing system of the brain.

Therefore, the cerebellar theory is now beginning to be considered part of the magnocellular deficit theory, due to its intimate anatomical and physiological links with the magnocellular system.

All Inclusive Cerebellar Deficit Theory

However Nicolson and Fawcett, the proponents of the cerebellar deficit theory argue that if one limits magnocellular deficit to the sensory or perceptual input stage, it does not explain the deficits that dyslexic children have outside the area of sensory and perceptual skills (Nicolson

and Fawcett, 1990). There is no magnocellular explanation for difficulties in time estimation, lowered muscle tone, classical conditioning, difficulties in detecting rhymes, which do not involve rapid processing. Moreover, there is no magnocellular explanation for normal speed of simple reactions, with the same response slowed significantly when a decision or choice needs to be made. There is also no magnocellular explanation for abnormal cerebellar activation in a motor sequence learning task.

At the cognitive level of explanation, the cerebellar deficit attempts to account for the automatisation deficits, which is what first implicated the likelihood of its involvement. It also attempts to account for the phonological deficit. Moreover, given the cerebellar role in speech, inner speech and speeded processing, it provides a natural explanation for the more recent 'double deficit hypothesis' which emphasises the presence of a lower speed of processing, reflected by a general naming speed deficit. Moreover, the question as to why children become faster as they mature reflects improved efficiency of the central processing mechanisms in which the cerebellum is centrally involved. Consequently, all three cognitive level hypotheses appear to be directly consistent with, and indeed, subsumed by, the cerebellar hypothesis.

Thus the proponents of the cerebellar deficit theory believe that the cerebellar impairment is an alternative or perhaps parallel mechanism to the magnocellular abnormality: it is possible that dyslexic children may show either or both of these deficits. They suggest that future research may reveal a magnocellular subtype, a cerebellar subtype and various mixed subtypes.

Possible Relationships between the Theories for Dyslexia

If one had to summarize the theoretical state of play, one might say that there are two specific theories, phonological and magnocellular, that are perhaps a little too specific to be credible explanations of the range of problems suffered by dyslexic children, and a third general theory, cerebellar, that is perhaps too general to account for the precise pattern of difficulties shown.

The phonological deficit theory suffers from its inability to explain the sensory and motor disorders that occur in a significant proportion of dyslexics, while the magnocellular theory suffers mainly from its inability to explain the absence of sensory and motor disorders in a significant proportion of dyslexics. The cerebellar theory presents both types of problems; it suffers from its inability to explain the sensory disorders in some, and the absence of motor disorders in other groups of dyslexics.

1.3 Event Related Potentials

1.3.1 <u>Background to Event Related Potentials</u>

Over a hundred and fifty years ago, the German physiologist DuBois-Reymond discovered that when a nerve was stimulated, an electrically measurable impulse was produced at the site of stimulation and then travelled at high speed down the nerve producing muscular contraction. He had discovered the 'nerve impulse', the basic mechanism of information transfer in the nervous system. This monumental discovery in 1848 gave birth to modern electrophysiology. Subsequently in 1875, the English physician Richard Caton first discovered spontaneous electrical signals in the brain. He achieved this by using DuBois-Reymond's electrodes to probe directly onto the surface of exposed brains of animals.

Fifty years later, inspired by Caton's work, the Austrian psychiatrist Hans Berger was the first to record electrical signals from the brains of humans. Berger named these recordings 'electroencephalogram' (EEG), derived from the Latin words *electro* meaning electrical signals, *encephal* meaning brain and *gram* meaning written. After more than a thousand recordings from the brains of 76 human subjects, he published a paper in 1929 providing a systematic description of the EEG. In his pioneering paper Berger wrote: "We see, in the electroencephalogram, a concomitant phenomenon of the continuous nerve processes which take place in the brain." The discovery of the human EEG by Berger was one of the greatest triumphs of neuroscience.

Thus EEG activity is the graphic depiction of the electrical potentials recorded by electrodes placed on the surface of the scalp. It is now widely assumed by electrophysiologists to be generated by the synchronous electrical activity of the millions of neurons of the brain, usually of the cerebral cortex, but sometimes of lower areas. This completely non-invasive procedure can be applied repeatedly in patients as well as in normal subjects without any risks or limitations. Hence it is now a widely used research and clinical technique, particularly useful for diagnosis in neurological and psychiatric disorders as well as for neurophysiological research.

In the 1950s, two decades after its discovery, the EEG technique was developed further to enable a great technical advancement in cognitive neuroscience: a technique to assess the sensory and cognitive processes in the brain was devised using 'event related potentials'.

The event related potential is the portion of the ongoing EEG pattern of the brain that is time locked to a specific internal or external occurrence: In other words, event related potentials are changes in 'potential' or voltage that are 'related' to a specific 'event'. This 'event' may be a sensory stimulus, a cognitive occurrence, or the execution of a motor response.

The synchronised feature of the ERP is its fundamental strength and represents its major advantage over the traditional EEG measure. This is because the EEG activity reflects a wide range of neural activities related to the myriad of self-regulating systems, sensory functions and cognitive functions ongoing in the brain at that time. This intermixing of sensory, cognitive, and other biological signals makes it difficult to separate out one factor from another. In contrast, because the ERP is 'time-locked' to the onset of a specific event, scientists are able to evaluate the relationship between the neuroelectrical response and the particular event. This relationship, in fact, can be resolved down to milliseconds or even fractions of a millisecond, if there were physiological processes that operate at this time scale.

Thus ERPs are regarded as manifestations of mental processing in the brain: they are thought to reflect the 'changes' in ongoing brain activity over time that occur in preparation for, or in response to, discrete sensory or cognitive events. Such changes have traditionally been measured as a change in the amplitude (voltage) of the wave at different points in its time course, or as a change in the latency (time) of certain peaks within the wave. The ERP, with its high temporal resolution, is now one of the most precise and preferred tools for measuring and comparing various aspects and speeds of human information processing.

1.3.2 ERP as an Assessment Tool

Development of ERP as an Assessment Tool

In the 1930s, there were a number of problems that reduced the effectiveness of the electrode plate technology for studying ERPs. Any minor movement of electrode plates over the skin, no matter how small, produced large artefacts that distorted or obscured the brain responses. To overcome this, scientists constructed a floater type of electrode that required a conducting paste, the electrolyte, to be placed between the skin and the electrode. The electrolyte allowed the small currents on the skin to be more readily transferred to the electrodes and thus recorded. This type of electrode is similar to many of the electrodes in common use today.

Although this latter approach reduced the electrode movement artefacts that often contaminated or obscured the minute evoked potential signal obtained from the contact or plate electrodes, a number of engineering and electrical difficulties continued to limit the potential success of this approach. In addition to problems in finding adequately conductive electrode materials one major difficulty lay in improving the low signal-to-noise ratio.

The ERP is small, only a few microvolts, in comparison to the EEG, which is about 50 microvolts. Thus, it is necessary to increase the discrimination of the ERP, or the 'signal' from the background EEG, or the 'noise'. That is, it is important to identify and isolate the very small events of relevance from the larger electrical and myographic events generated by other body biosystems. This could be considered analogous to the problem of distinguishing between small pond ripples caused by one pebble (the event) from the larger ripples created by wind, rain, and other factors (other neural processes occurring in the brain at the time).

In the mid-1940s, Dawson devised a technique to improve the signal-to-noise ratio of the ERP through the use of a capacitance-based computer analogue that summed repetitively elicited event-related potentials. By adding together and 'averaging' electrical signals recorded on successive trials, Dawson's device calculated summed event-related potentials that reflected the repetitive information contained in the evoked potential from one time to the next or from trial to trial. These summed or averaged ERPs represented the brain electrical activity common to all of the ERPs collected during a recording session. On the other hand, the non-repetitive signals that reflect random signals or noise failed to contribute systematically to specific portions of the accumulating sum. In other words, in all cases the samples are selected so as to bear a constant temporal relationship to an event and since all those aspects of the EEG that are not time locked to the event are assumed to vary randomly from sample to sample, the averaging procedure should result in a reduction of these potentials leaving the event-related potentials visible.

The modern EEG and ERP data collection systems offered by many companies today are logical extensions of Dawson's original idea to sum and average event related potential responses in order to improve the signal-to-noise ratio. Such 'low noise' averaged ERPs provide investigators the opportunity to see the direct effects of the stimulus and the subject's processing of that stimulus in the subject's brain wave.

An additional issue important to the development and evolution of such cortical electrophysiology is the development of the analysis techniques useful for evoked potential data. Analysis procedures have developed at an excruciatingly slow pace throughout the past century, as evidenced by the fact that the most widely used methods of data analysis today (i.e. peak amplitude and latency measures) date back to Caton in the late 1800s. However, within

the past two decades a number of recent developments in analyses and ERP technology have emerged, especially since the development and more widespread use of personal computers.

Biobehavioural Basis of ERP Assessment

The ERP is generally believed to reflect post-synaptic dendritic potentials (Allison et. al., 1986). Even so, the information recorded at the scalp cannot capture all of the generated electrical activity. For the signals to reach the scalp, they must be produced by fairly extensive sets of activated neurons whose firings must to some extent overlap each other in time. And even so, not all signals reach the scalp for a variety of reasons. It is often difficult to detect a signal because the distance from the cortical regions generating the signal to the scalp may often be too great relative to the signal's strength. Signals that originate within the brain must travel through a variety of tissues of different densities, conductivity, and composition (e.g., neurons, glial cells, fibre tracts, cerebral spinal fluid, bone, muscle) before they reach the recording electrode placed on the scalp of an individual. In addition, the orientation of the cortical columns generating the signal may also contribute to whether a signal reaches the scalp. If the columns are perpendicular to the scalp, the likelihood of the signal reaching the scalp is good. On the other hand, if the column is parallel to the scalp or at some other angle to it, the signal may simply not project to the scalp or may project to the scalp some distance away from the electrode that is immediately above it.

The actual ERP signal that is finally detected at the scalp is not by any means an exact and completely stable pattern reflecting only those discrete neural events directly related to the evoking stimulus, the task, or the subject's state. Clearly, the ERP is only a by-product of the brain's bioelectrical response to such an event that begins as the stimulus information is transformed by the sensory systems. The signal then progresses through the brainstem into the midbrain and then progresses upward into the higher centres of the brain. Consequently, the final version of the ERP recorded at the scalp is a composite of a variety of complex factors, only some of which may actually relate directly, or even indirectly, to the variables under manipulation in the experiment.

Electrode Placements during ERP Assessment

The choice of placement of electrodes on the scalp is an important step in ERP recording. The choice is often driven by hypotheses concerning the relationships between the functioning of

different brain regions and the cognitive operations or processes assumed to occur in those areas.

Restrictions of Electrodes

Unfortunately, for a variety of reasons, any single scalp electrode does not simply detect information that originates within the brain immediately below that electrode. Instead, each group of neurons creates what is called a "dipole field" that generates positive electricity in one direction (e.g., toward the surface of the cortex) and negative electricity in another. This dipole field can be thought of as a flashlight with two lenses, one pointing up and the other pointing down, each creating a cone of light (actually electricity) that spreads outward until it reaches the surface of the body. Because of this spread of electricity, called 'volume conduction', an electric potential at a given scalp site may not be restricted to nearby brain tissue, but could reflect activity of brain tissue that is far away.

Making matters worse is the fact that the human cortex is highly convoluted, or wrinkled. This means that the volume conduction (where the flashlights point) will be determined by the wrinkles, and these are highly variable from one person to the next. This is why advanced "anatomically constrained" source analysis methods use the subject's actual cortical surface (from the MRI) to estimate how the wrinkled electrical field can be "unfolded" to relate it back to specific regions of cortex.

Another complication is that the volume conduction is changed by the resistivity of brain tissues to passing electrical current. For example, because the skull is so thick and hard, it is particularly resistive, such that a dipole field 'spreads' when it passes through it. Advanced source analysis methods must take this into account, using specific measures or estimates of skull conductivity for each region of the head. This is especially true for infants and young children because their highly variable skulls are incompletely calcified and contain both fontanels and sutures between the skull bones

What these factors should make clear, to reiterate an important point, is that electrodes on the scalp do not necessarily measure electrical activity generated by neurons immediately below those electrodes. Rather, scalp electrodes can detect changes in electrical discharges that originate deep within the brain as well as from active areas in other brain regions and the opposite hemisphere.

Electrode Sites

A variety of strategies have been used to select electrode placements sites. Reviews of the ERP and EEG literature suggest that approximately half of the studies use the 10-20 System designed for use with adults and reported by Jasper (1958). This technique relies on proportional measures of the head to determine electrode placements and is useful in attempting to replicate placements done across studies using the same technique. Development of a similar system has been attempted with infants (Blume, Buza, & Okazaki, 1974). However, a number of factors, such as a small sample size and the lack of measurements from both hemispheres from the same infants limit the usefulness of the Blume et. al.. approach as a standardized system for electrode placement in infants or children. However, it is clear even from these limited data that the 10-20 system in use for electrode placement in adults does not overlay the same cortical regions in young infants. For example, as Blume et. al. note, central leads in infants were found to lay over the post central gyrus (sensory) whereas such leads were over the precentral gyrus (motor) in adults, two very different functional areas within the brain. In infants the inferior frontal electrode actually lies inferior to the frontal lobe as opposed to over that area in adults. Additional points of discrepancies were noted between infant and adult placements. These discrepancies further raise issues regarding the legitimacy of comparing recordings between infants, children, and adults.

Placement of electrodes on the individual's head is usually driven by hypotheses concerning the relation between different anatomical brain regions and the cognitive processes assumed to be engaged by the evoking stimulus and the characteristics of the experimental task. For example, the brainstem evoked response (BSER), which is generally used as a screening technique for sensory processing, is thought to reflect brainstem responses that reflect detection of the brief stimuli presented to the participant. This testing procedure involves the placement of only one active electrode at a central point (Cz) mid-way between the left and right ears as well as midway between the upper ridge on the nose (nasion) and the base of the bump at the central back portion of the skull (i.e., the inion). In research investigating more complex, higher order processing, such as language processing, electrodes are typically placed over a number of brain regions thought to be actively involved in language perception (itemporal lobes) as well as language integration (temporal-parietal areas), and language production (frontal brain regions).

Typical ERP studies place electrodes over bilateral frontal, temporal, central, parietal and occipital areas of the brain. This placement is assumed to provide information concerning left versus right hemisphere responses to the evoking stimuli, and information within each hemisphere concerning functioning of different brain areas. Unfortunately, as noted above, the scalp electrode does not only detect responses from the brain area immediately below the scale location. For example, because of volume conduction, the T3 electrode site may pick up not only activity produced immediately beneath it in the left hemisphere temporal region, but also

activity produced in other adjacent brain areas. Thus, caution must always be used in attributing ERPs recorded at one electrode site to a single area of the brain. In the last few years, a host of computer programs, such as BESA, have developed which, when used in conjunction with theoretical model, offer a means to address questions concerning brain regions responsible for the generation of such signals.

Referencing Electrodes

The ERP scalp activity recorded at any one electrode is typically referenced to other recording sites. These referenced recording sites are selected because they are either less electrically active and consequently of less interest to the investigators (such as the tip of the nose, mastoids, or ear lobes) or are sites on the scalp that may be characterized by comparable but different levels of electrical activity. These latter reference sites are chosen so that the investigator can more directly examine the electrical differences between those recording sites and the other scalp sites. More recent techniques have used a calculated average reference that is based on the average of activity recorded at all electrode sites. A limitation of the average reference method is that it is only accurate when there are a large number of electrodes, and they completely cover the head surface including the face and neck (Junghöfer, et. al.., 1999).

Eye Movement Artefact Electrodes

In addition to scalp and reference electrodes, additional electrodes are usually placed at supraorbital (above the middle of one eye over the eye brow) or suborbital (approximately 2 cm below an eye on the upper portion of the cheek) and canthal (to the side of the head away from the eye approximately 2-3 cm) positions in relation to one of the participant's eyes to assist in the detection of artefacts due to horizontal and vertical eye movements. Such eye movement artefacts or blinks can produce large electrical signals that can distort ERPs recorded at other adjacent electrode sites, even those positioned towards the back of the head (Junghöfer et. al.., 2000).

Test Procedures in ERP Assessment

ERP Acquisition

The actual ERP recording procedure involves a number of steps. First, an individual's head is measured and positions are marked to indicate where the key or reference electrodes are to be placed. Next, the electrode net is soaked in electrolyte solution and carefully placed on the subjects head to align with the designated positions. The locations are usually chosen according

to the International 10-20 system (Jasper 1958), such that between-laboratory and between-experiment comparisons are possible. The electrodes are connected via wires to amplifiers that increase the ERP signal by 20,000 to 100,000 times. Given that ERPs are generally very small, of the order of 5 to 10 μV in adults, such amplification is required to provide enough definition of the waveform for further analyses. Amplifiers used in recording systems also contain filters that screen out some of the recording system noise, the ambient electrical noise in the environment as well as the biological background noise that subject's carry about with them that the investigator does not want to study. The outputs from these amplifiers are connected in turn to a computer that collects the ERPs from each electrode for each stimulus presented.

Stimuli Presentation

Once all the electrodes are in place and connected to the amplifiers and the computer, the stimuli can be presented when the participant is in a reasonably restful state. Each ERP is made up of a number of time points beginning from stimulus onset until the end of the sampling period. Thus this time period may range from 0 ms (the point in time when the stimulus begins) until 1000 or even 2000 ms after this stimulus onset time. The duration of the ERP is generally up to the investigator but is usually informed by what others have done before in similar studies or with comparable subject populations. In addition, investigators can examine the ERP to determine where the variability in the ERP (as evidenced by the standard deviation at each time point) begins to increase and decrease. Usually there is little variability at the very beginning of the ERP as the stimulus first begins to work its way through the nervous system. There also is a decrease in the size of the standard deviation as the ERP returns to background EEG activity as the time sync between the stimulus and the brain breaks down.

Once the duration of the ERP is decided, the investigator must decide how frequently to sample the ERP signal across time following the onset of the stimulus. Sampling is necessary because brainwaves are analogue (continuous) signals, and analyses can be performed only on digital (sampled) signals. As with duration, the decision to select a certain sampling rate can also be based on studies investigating similar phenomenon or studies of similar populations. Most studies generally use sampling rates of 4 or 5 ms. If an ERP were sampled at 4 ms intervals, 250 data points would be collected for each ERP during that 1000 ms period. The 250 points from each of these ERPs from each participant for each electrode can then be submitted to subsequent analysis.

ERP Analysis

Because of the inherent variability in the ERP that results from moment-by-moment changes in the physiology of an individual, researchers have a variety of means at their disposal to analyze the collected ERPs. Usually, the ERPs are first recorded to discrete events (e.g., shapes, pictures, sounds, words) and then, following artefact rejection, averaged together in order to build stable waveforms and improve their signal-to-noise ratio. The logic is that the resulting averaged response is more likely to contain the recurring activity that reflects the processing of the stimulus from one time to the next. In contrast, the non-stimulus related activity that is not time-locked to the onset of the stimulus is expected to average out or be minimized in the averaged waveform of the ERP. Once averages are obtained, they are subjected to a variety of analysis approaches. Traditionally, the technique of choice has involved amplitude measures taken from various peaks in the waveform. These amplitude measures may be made between two adjacent peaks of opposite polarity (e.g., measuring the voltage difference between the most positive peak and immediately preceding or following negative peak), a process referred to as a "peak-to-peak" measure or between the average pre-stimulus baseline signal and a specific positive or negative maximum peak amplitude, a process refereed to as a baseline-to-peak measure. Subsequent analyses of the ERP are then conducted on the averaged waveforms. These analysis approaches have a range of options including amplitude and latency (reaction time) measures, area measures, discriminant function procedures, and other multivariate approaches

Strengths of ERP as an Assessment Tool

ERPs have a number of strengths as an assessment tool. For example, the procedure can be applied to participants across multiple age groups. Few techniques currently in use can be applied from the newborn period though the adulthood period. Consequently, ERPs are useful for making direct comparisons between infants and adults to address a variety of developmental questions. Although the wave shapes of the ERPs change from infancy to adulthood, one can assess whether brain responses recorded at different ages discriminate reliably between different stimulus, participant, and task conditions obtained concurrently or a different time periods. Moreover, the ERP procedures can be used to obtain response information from participants who have difficulty responding in a normal fashion (as in the case of individuals with brain damage) or who cannot respond because of language or maturity factors (as in the case of young infants and children). ERPs also are recognized as providing information concerning both between hemisphere differences as well as within hemisphere differences in the brain's electrical activity under specific stimulus conditions. Further, the ERP procedure is useful for providing time-related information. It can indicate the onset of one stimulus relative to another and provide information about the different points in time when such information is detected and processed.

Comparison of ERP to Other Techniques for Assessment

Because of their excellent temporal resolution and correlations with specific cognitive/linguistic activities, ERP procedures offer advantages over other brain imaging procedures such as EEG, BSER, Positron Emission Tomography (PET), and functional Magnetic Resonance Imaging (fMRI). For example, although the classic EEG measure provides some indication of clinical states such as epileptic seizures, it does not resolve cognitive activities to the level offered by the ERP (Callaway, Tueting, & Koslow, 1978). Thus, while frequency analyses of EEG may indicate attentive or inattentive states (as in the case of alpha activity) or an increase in workload (as in the case of beta activity), it is unable to resolve changes in stimulus parameters, decision-making, or short-term memory activity. Likewise, although BSER information can reflect initial sensory detection and brainstem response to very brief evoking stimuli, the temporal duration of the BSER (approximately 10 - 15 ms) precludes its use for studying longer and later occurring cognitive processes involved in these activities. In addition, although PET and fMRI procedures are good at identifying metabolic brain changes associated with cognitive processes (Shaywitz & Shaywitz, 1993), they are as yet unable to resolve the temporal order of these processes or the more discrete decisions regarding the processing of stimuli. Moreover, the expense and complexity of setting up an ERP lab is considerably less than the multiple millions of dollars required for the PET, magnetoelectroencephalography (MEG) and functional fMRI procedures. Finally, the ease of ERP application and testing may be less formidable than other techniques to young participants and their parents.

Constraints on the Use of the ERP for Assessment

Although ERPs offer many advantages as an assessment technique, there are certainly limits to the interpretation of the results of ERP studies just as there are with other techniques, physiological or behavioural. First, ERP studies share the basic limitations indigenous to all experimental approaches - - one must make a leap from the data obtained in an experiment to the interpretation of the data.

Second, although there may be something seductive in recording electrical currents thought to originate "directly from the brain", the reality is that the specific origins of these currents and the dynamics that lead to their particular presence at the scalp remain somewhat beyond our understanding at this time. The measurement-based placement system reflected by the 10-20 system tried to standardize electrode placement across participants so that placements roughly approximate scalp locations to brain regions. However, for reasons already noted, attributing signals from scalp locations to specific brain regions is fraught with problems. Further, the

scalp electrode does not only detect information that originates immediately below that electrode position in the brain. Thus, there are limits as to how far one can speculate about the brain origins of the scalp recorded ERP signal. Fortunately, the relationship between ERP signal and cognition and behaviour is less tenuous. Indeed, the linkage between the ERPs and specific behaviours is not accidental and can be effectively exploited in carefully designed and executed experimental paradigms as linked to current and later developing behaviours.

A third major limitation concerns the validity of comparing ERP waveform characteristics across different developmental periods. Do similar paradigms used with adult and infant populations most likely do not tap the same abilities, given the large cognitive and linguistic differences that exist between infant and adult populations or even between infants at markedly different times in development. Based on a host of neuroanatomical studies, we know that the brains of infants differ markedly from adults in terms of neurogenesis, dendritic development, and myelination, to mention only a few characteristics. Such differences in neural structure state, as well as in the differential development of brain structures across ages, limit in some ways our ability to interpret findings from groups that are developmentally disparate. Equally plausible is the alternative explanation that these ERP components tap very different cognitive or physiological mechanisms that simply generate such similarities. Just as different connectionist models might generate similar behaviours, signals generated within the brain at different stages of development in combination with different cortical densities could produce similar brain responses when recorded at the scalp. Such similarities (or differences), consequently, by themselves do not necessarily mean that the same brain mechanisms are functioning at the same level in theses different populations.

1.3.3 Nomenclature for ERP Components

The human ERP reflects a complex interactive process between an individual and the environment. Different parts of this waveform may specifically relate to different aspects of the environment, to different cognitive interactions within the brain, or to different response systems (Picton, 1980). As a result, ERP components have been defined in different ways.

Waveform Based

The 'waveform based' means of identifying ERP components involves the visual peaks in the recorded waveform. Such peaks can then be named according to their sequence (in numerical

or alphabetical order) and polarity (Picton *et. al.*, 1974). The 'fast' components of the response are identified as a series of small positive waves recorded in the first 10 ms and numbered sequentially using Roman numerals. The 'middle' latency components occur in the 10-50 ms range and are identified using polarity and a combined numerical and alphabetical sequence. The 'slow' components occur between 50 and 500 ms and are identified as P1, N1, P2 and N2.

Obviously a sequential nomenclature is open to criticisms of confusion and complexity. Thus a latency nomenclature for the peaks has also been proposed wherein components are identified by their polarity and peak latency (Donchin *et. al.*, 1977). In this nomenclature, the wave V of the fast auditory response would be called P6 and the component N1 would be identified as N90. This is more accurate than the sequential nomenclature but its very precision can, at times, cause problems. The latency of a component may vary with the intensity or rise time of the stimulus, or with the time required for perceptual processing. Wave V varies in latency from 5.5 - 8.5 ms as intensity decreases without obviously changing its identity, and the late positive component of the sensory evoked potential related to perceptual decisions may vary in peak latency from 300 to 900 ms depending on the difficulty of the decision. To allow for such variance, theoretical components may be identified by their characteristic latency, and a superimposed line used to show that such identification is theoretical rather than observational.

Anatomy Based

The 'anatomy based' means of identifying ERP components is based on the output of a particular anatomical generator structure or system. Thus the parameter that is considered in the identification of ERP components is the location of recording electrodes (Picton, 1980). For instance, part of the primary cortical somatosensory response is generated in the posterior wall of the Rolandic fissure, creating a dipole that is parallel to the scalp surface. The same ERP component can therefore be recorded from the anterior scalp regions as a positive wave with a peak latency of 20 ms and more posteriorly as an N20 wave. Furthermore it is quite possible that components with the same polarity and general latency recorded from different scalp areas, such as the negative components at around 150 ms recorded in response to visual stimuli from the vertex and from the occiput, reflect separate and distinct underlying components. Based on this parameter, Näätänen and Picton defined a component to be: "the contribution to the recorded waveform of a particular generator process, such as the activation of a localized area of cerebral cortex, by a specific pattern of input. Whereas the peaks and deflections of an EP can be directly measured from the average waveform, the components contributing to these peaks can usually be inferred only from the results of experimental manipulation."

Process Based

The 'process based' parameter for identifying ERP components is based on those aspects of the waveform associated with a particular behavioural or cognitive process. Based on this parameter, Donchin and his colleagues proposed that a component is "a source of controlled observable variability (such that) we try to dissect morphology in term of the manipulated variables. Different neuronal aggregates might be activated at different times at different extents in different forms by different values of our critical variables. ERP data are presumed to represent the activity of intercranial neuronal aggregates. Though careful experimental dissection of the waveforms it should be possible to partition the observed variance of the ERP waveform into sources of controlled variance we call components."

For some ERPs, theoretical labels have been assigned that identify the hypothesized functional roles of the components, such as "mismatch negativity", "processing negativity", or "readiness potential". In other cases, polarity-latency labels such as P300 or N400 have been used in a theoretical sense, referring not to a waveform feature but to a psychophysiological entity with specific functional properties (Muller Gass et. al., 2002).

While the 'anatomy based' definition by Näätänen and Picton places particular emphasis on a components distinct intercranial generation, this is not irrelevant in the 'process based' definition by Donchin and colleagues. However, their more functional definition does not consider the localization of the components source to be as relevant to the definition of a component. Thus, the locus of generation is not a necessary aspect of a component's definition properties (Muller Gass et. al., 2002).

In their report on Publication Criteria for studies of ERPs, Picton and his colleagues point out that "an important distinction needs to be made between observational terminology, which refers to the waveform features measured in a given data set, and theoretical terminology, which designates ERP components that represent particular psychophysiological processes or constructs". In the present work, ERP components have been considered to be theoretical terms that are defined in the manner proposed by Donchin and colleagues. Thus, we take scalp distribution to be a defining attribute of a component, the other two defining attributes being the morphology of the component and its sensitivity to experimental variables. This approach does not allow components to "shift their distributions" because, by definition, different distributions imply different components.

Task Based

Perhaps the most useful classification at present is the 'task based' classification, based on those aspects of the ERP associated with particular antecedent conditions and experimental manipulations. This classification usually depends upon the relationship of the component to external stimuli.

ERPs can be classified as evoked or emitted. 'Evoked potentials' are the ERPs that follow a physical stimulus whereas the 'emitted potentials' occur in the absence of any evoking stimulus (Picton, 1988). Emitted potentials may be associated with some psychological process such as the recognition that a stimulus has been omitted from a regular train, or with some preparation for an upcoming perceptual or motor act.

The ERPs can also be classified as exogenous or endogenous. 'Exogenous' EPs are determined by the physical characteristics of a stimulus whereas 'endogenous' EPs are determined by the psychological or cognitive significance of the stimulus, that is, the psychological or cognitive demands of the situation (Sutton *et. al.*, 1965; Donchin, Ritter and McAllum, 1974). The emitted potentials, being related to psychological processes rather than physical stimuli are, by definition, endogenous.

The exogenous waveforms can be further divided into 'transient', sustained and 'steady state' responses. Transient potentials are elicited by a stimulus change whereas sustained potentials occur during the continuation of a stimulus. Steady state potentials are evoked by stimuli of sufficiently high repetition rate that there is an overlapping of responses to form a continuous waveform with constant amplitude and phase relationship to the repeating stimulus.

The endogenous components of the human ERP can be further classified into 'preparatory' and 'integrative' potentials. The preparatory potentials are those related to specific motor activity such as the 'readiness potential' that occurs prior to self-paced motor actions. The integrative components are related to complex human perceptual activity, and include waveforms such as the late positive component of the sensory evoked potential and the contingent negative variation.

Variance Based

The actual component structure of an ERP waveform may not correlate with visually recognisable peaks. It is impossible to determine whether these peaks represent discrete

physiological events or whether they are recording artefacts, resulting from several overlapping components of similar latency. Probably the most important factor in the definition of ERP components is the functional relationship of a part of the waveform to experimental variation (Donchin, Ritter and McCallum, 1978). Any distinct component of the waveform must be affected by experimental manipulation in a manner unique from any other component. Such an approach to component identification lends itself to objective mathematical evaluation. An analysis of the principal components of a waveform yields a series of components contributing independently to the recorded variance during an experiment (Squires et. al., 1977). Such a technique can be extremely helpful provided that its limitations are recognized. Changes in the latency of a component and non-linear interactions among different components can reduce the effectiveness of the procedure. Furthermore, such an analysis will not identify components of the waveform that remain unaffected by the limited experimental manipulations studied. Nevertheless, such techniques, when applied with appropriate judgement and imagination, can greatly further our understanding of the structure of scalp recorded ERP and its relation to human information processing.

1.3.4 Description of ERP Components

Exogenous Components

All parts of a sensory system, from the receptor to the association areas of the cerebral cortex can contribute to the sensory evoked potentials that are recorded from the human scalp. In terms of perceptual processes previously described in Section 2.2.3, the exogenous components of the ERP trace could be thought to represent the early *descriptive* processes of perception.

Auditory P1 Waves

The cochlear microphonic potential generated by the hair cell receptors of the cochlea can be recorded from electrodes on the mastoid of auricle. A series of vertex positive waves recorded in the first 10 ms after an abrupt auditory stimulus represents the activation of the cochlear nerve and brainstem auditory nuclei. Between 10 and 50 ms there is a complex response recorded from the scalp that reflects auditory activity in the thalamus and cortex as well as possible scalp muscle artefacts (Picton, 1980).

The slow components of the transient auditory response, such as the P1 wave, probably derive from the activation of various areas of the primary and association cortex. Auditory sustained

potentials can be recorded from the human scalp in response to sounds of more than a few tenths of a second in durations.

Visual P1 Waves

Visual evoked potentials from the neurons of the retina may be recorded as the electroretinogram using peri-orbital electrodes. In the occipital regions of the brain, a flash stimulus elicits a complex series of waves beginning at around 25 ms. The morphology of this response in the 50-250 range is quite dependent upon the contrast and pattern of the visual stimulus (Picton, 1980).

When a stimulus involves mainly a change in pattern without any change in the intensity of the stimulus, the morphology of the occipital response becomes much simpler. In response to a reverse checkerboard, for example, there is a simple bi- or tri-phasic response containing a distinct positive component, the P1 wave, in the 80-120 ms range that is best recorded using a frontal reference electrode. In response to rapidly repeating visual stimuli, a multitude of steady-state responses can be recorded from the occipital region

Mesogenous Components

In all sensory systems, there is a large complex of waves recorded from the vertex region with latencies in the 50-250 ms range. This response to a stimulus change has often been termed as vertex potential. The morphologies and scalp distributions of these responses in the various sensory modalities are quite similar, suggesting that vertex potential reflects similar though not necessarily identical underlying processes in each sensory system. There are large interactions among the responses to stimuli in different sensory modalities, suggesting that the vertex potentials derive from generators activated by all sensory modalities. It has therefore been suggested that the vertex potential might reflect the convergence of sensory information from different sensory modalities onto areas of association cortex particularly in the frontal lobe. In terms of the perceptual processes described in Section A.1.2 of the Appendix, the mesogenous components could be assumed to represent some of the *integrative* processes of perception.

It is probable that several underlying sources contribute to the scalp-recorded waveform in the latency range of the vertex potential. This concept of several underlying components raises the possibility that the so-called mesogenous components represent overlapping exogenous and endogenous components of the ERP. Whether there are distinct components in this latency range that are related on the one hand to stimulus parameters and on the other hand to

psychological factors is, however, still not fully known. If indeed there are such overlapping components, one can hypothesize that they might reflect a general comparative process whereby incoming exogenous information is related to relevant endogenous memories prior to its interpretation.

N1 Wave

Latency and Scalp Distribution

The N1 is a negative evoked potential with an average latency of 100-300 ms (**Breznitz and Meyler, 2003**).

Functional Generator

This wave is associated with early attention processes (Leppanen & Lyytinen, 1997; Oades, Dittmann-Balcar, & Zerbin, 1997).

A model of attention in auditory processing proposed by Näätänen, distinguishes two sensory detector systems. First, a transient detector system, which is sensitive to changes in stimulus energy, such as stimulus onset and offset and second, a permanent feature detector system, which is responsible for the decoding of the physical stimulus features, such as pitch and intensity, and which feeds its output into sensory memory. According to Näätänen, the output of the transient detector system is reflected in the N1 wave of the auditory vertex potential.

P2 Wave

Latency and Scalp Distribution

The P2 is a positive waveform with an average latency that ranges from 150-300 ms depending upon modality and stimulus parameters (Breznitz and Meyler, 2003).

Functional Generator

This component is thought to reflect both exogenous and endogenous processing (Dunn, Dunn, Languis, & Andrews, 1998; McDonough, Warren, & Don, 1992). According to recent research, it is thought to reflect a general evaluation and elaboration of the stimulus. Specifically, it is held to index mechanisms of feature detection (Luck & Hillyard, 1994), selective attention

(Hackley, Woldorff, & Hillyard, 1990), and other early sensory stages of item encoding (Dunn et. al.., 1998).

Mismatch Negativity

In 1978, Näätänen and his colleagues first described the Mismatch Negativity (MMN) component of the ERP trace (Näätänen, 1978). Since then, these last 25 years have seen a phenomenal surge in its application in the research of auditory processing disorders.

Latency and Scalp Distribution

In adults, the MMN consists of a negative potential over the frontocentral scalp and a positive potential beneath the mastoids, with an average latency of 50-250 ms (Näätänen et. al., 1978). MMN has been reported to be quite stable during development. Studies investigating school children reported similar MMNs as for adults, but with slightly longer latencies (Gomes et. al.., 1999; Gomes et. al.., 2000; Gomot et. al.., 2000; Shafer et. al.., 2000). Furthermore, younger children had longer latencies than older children (Gomes et. al.., 1999; Gomot et. al.., 2000; Shafer et. al.., 2000).

Particularly in children, this early MMN can be followed by a late MMN peaking between 300 and 500 ms (Korpilahti et. al., 1995; Korpilahti et. al.., 2001). However, most recordings apply shorter ITIs of around 500 ms to enable the presentation of sufficient numbers of rare deviants before the subjects experience any tiredness effects. Hence, the late MMN is often excluded from the ERP trace (Schulte-Körne, personal communication). The functional relationship between the early and late MMN is still unknown, and warrants further investigation.

Elicitation Criteria

The MMN is elicited using a 'passive oddball' paradigm. The 'oddball' paradigm involves the presentation of unexpected or infrequent stimuli (the 'oddball') randomly interspersed among more frequent stimuli (Squires, 1975). The term 'passive' refers to the fact that the subject remains passive to the stimuli and does not need to pay any attention or give any response to the stimulus. Stimulus parameters such as inter-stimulus interval, stimulus duration, stimulus sequence, and the probability of occurrence of the deviant stimulus affect the amplitude and latency of the MMN: the wave gets smaller or even disappears as the degree of deviance is reduced (Näätänen et. al.., 2001). Thus, in the auditory modality, the MMN is elicited by changes in frequency, intensity of duration of tone stimuli, or changes in complex stimuli such as complex tone patterns of phonemes (Schulte-Körne, 1999).

Anatomical Generator

The main neural generators of the MMN are located bilaterally in the superior temporal plane of the auditory cortex, with some evidence for additional frontal sources (Alho, 1995; Näätänen *et. al.*, 2001a) for the auditory thalamus and hippocampus (**Kraus, 1993**).

Functional Generator

The MMN occurs when there is a change in a repetitive sequence of stimuli, and thus appears to reflect a process specific to 'stimulus change' (Näätänen, 1978). It is considered an index of the functioning of the auditory sensory memory, since it seems to be generated by neural traces carrying the central sound representation (Näätänen *et. al.*, 2001a).

According to Näätänen's model of attention in auditory processing, which distinguishes a transient (sensitive to stimulus onset and offset) and permanent feature (sensitive to pitch and intensity) detection system, while the output of the transient detector system is reflected in the N1 wave, the outcome of the comparison between the decoded features of an incoming (deviant) stimulus, and the stored memory trace of the preceding (standard) tones is reflected in the MMN wave. The functional role of the late MMN and its relation to the typical MMN still needs to be determined.

Two aspects of MMN are extremely relevant and have made it the most widely tested exogenous component of ERP with a plethora of clinical and research applications. Firstly, the MMN has been obtained in response to changes in a number of physical features of the auditory stimulus including frequency, intensity, duration, as well as spatial and phonemic changes. Moreover, it is extremely sensitive to very fine stimulus differences, occurring even when the stimulus differences are near the psychophysical discrimination threshold. In fact it has been found to occur when the difference between the standard and deviant stimuli is as small as 8 Hz or 5 dB. More complex stimuli generally elicit a more robust MMN. Thus MMN provides a neuronal representation of the discrimination of numerous auditory stimulus attributes.

Secondly, the MMN is elicited passively. That is, it does not require attention or a behavioural response to occur. Indeed, it has been obtain during sleep in infants and adults, and during sleep and anaesthesia in animal models. Hence, although the disadvantage for MMN is its fairly low signal to noise ratio, making the acquisition of a large number of trials necessary, its clear advantage in comparison with behavioural methods is that it can be recorded without the subjects active involvement in the task and therefore, it provides a direct means for measuring

auditory discrimination accuracy without task related factors such as attention or response strategies.

As such, the MMN provides an accurate and objective neuronal representation of automatic pre-attentive stimulus discrimination and can be applied to the assessment of auditory processing disorders. Various neuropsychiatric and neurodevelopmental disorders are accompanied by abnormal MMN to deviant stimuli. For example, children with autism with temporal lobe impairment show longer latency and lower amplitude of the temporal component of the MMN (Seri et. al. 1999) and a frontal component of the MMN was attenuated in subjects with schizophrenia (Baldeweg et. al., 2002) and with ADHD (Kemner, 1993) and dyslexia (Baldeweg et. al. 1999, Kujala and Näätänen, 2001).

N2 Wave

The N2 is a negative event-related component also held to represent both an endogenous and an exogenous response (Tonnquist-Uhlen, 1996).

Latency and Scalp Distribution

The average latency of the N2 is about 200-400 ms depending upon scalp location and modality.

Functional Generator

Some studies have observed that this negativity is modality specific in its scalp distribution and might therefore reflect the actual recognition of the informative target within a specific sensory channel (Simpson, Vaughan and Ritter, 1976, 1977). Other studies have suggested that the N2 is associated with focused attention as well as stimulus evaluation, particularly stimulus classification and discrimination (Han, Fan, Chen, & Zhuo, 1999; Näätänen & Picton, 1986; Novak, Ritter, Vaughan, & Wiznitzer, 1990; Ritter, Simson, Vaughan, & Macht, 1982; Vaughan & Kurtzberg, 1992). The amplitude of the N2 component has been found to relate inversely to the probability of either attended or unattended infrequent deviations of the stimulus (Ritter, 1984).

Endogenous Components

After 200 ms there are a large number of waves related more to the cognitive context than to the physical characteristics of the stimulus (Picton 1980). This variety of electrical responsiveness

probably reflects the general adaptability of the human brain in the processing of sensory information to behavioural response. In terms of the perceptual processes described in section 1.2, the endogenous components can be considered to represent the 'inferential' processes of perception, and later more complex cognitive processes.

P3 Wave

In 1965 Sutton and his colleagues reported the discovery of the P3 wave. It is the most prominent and also the most extensively studied cognitive component in the prototypical ERP trace. It follows a point in time when task-relevant information becomes available to a subject regardless of whether or not that point in time is indicated by a specific stimulus.

Latency and Scalp Distribution

The P3 is a symmetric positive wave with maximal amplitudes over the midline central and parietal regions of the scalp (Oken, 1989), and with a latency that varies from 250 to 600 ms depending on stimulus and subject parameters (Polich, 1999).

Elicitation Criteria

Virtually any sensory modality can be used to elicit the P3 response (Oken 1989). In descending order of clinical use these are auditory, visual, somato-sensory, olfactory or even taste stimulation. The P3 wave is similar in morphology and scalp distribution regardless of the sensory modality of the information. However, the latency of the P3 wave differs with each modality. For example, in auditory stimulation, the latency is usually shorter than in visual stimulation (Katayama and Polich, 1999). This suggests that the sources generating the P3 wave may differ and depend on the stimulus modality (Johnson 1989).

The most commonly used paradigm to obtain the P3 is referred to as the active 'oddball paradigm' (Oken et. al., 1993). As mentioned previously, the oddball paradigm involves the presentation of unexpected or infrequent stimuli randomly interspersed among more frequent stimuli (Squires, 1975). In most studies the unexpected stimuli can differ from the more common stimulus in terms of a physical characteristic, or may simply be the absence of a stimulus among a train of regularly spaced stimuli, or may be a change in the inter-stimulus interval among a train of regularly spaced stimuli (Oken, 1989). The 'active' term refers to the fact that the subject must actively attend to the stimulus.

Such an active method that augments the P3 and is generally used in conjunction with the oddball paradigm consists of the selective choice reaction task, which requires selectively attending and responding to the task relevant target stimuli while ignoring the non-target stimuli. The response can be a given motor response, typically pressing a button, or just a mental counting to target stimuli. A P3 will be seen following a target but not a non-target stimulus.

It is important to note that these two factors, first stimulus infrequency or unexpectability, and second, attention or task relevance, both operate independently. In fact, there is evidence that they produce different P3 components (Squires et. al., 1975; Courchesne et. al., 1975). The 'P2' is elicited by an infrequent stimulus, independent of task relevance, occurs slightly earlier and has a more frontal distribution. Compared to this, the 'P3' component is best elicited by attending to task relevant stimulus (Squires et. al., 1975), occurs later and has a more parietal distribution (Squires et. al., 1975). Presumably, the routinely obtained P3 represents a sum of these two component waves.

Anatomical Generator

The generator site of the P3 is not known with certainty. This, in part, is related to the fact that there is more than one P3 component. However, even though the exact neural origins of the P3 are still being sought, depth electrode recordings and magnetic field studies in humans suggest that at least some portion of the P3 is generated in the medial temporal lobe, most likely including the hippocampus (Halgren et. al., 1980, McCarthy et. al., 1982).

Functional Generator

As noted earlier, unexpected events that are relevant to the subject's task elicit large P3 waves and the amplitude of the P3 decreases with increases in the probability of the eliciting stimulus (Duncan-Johnson and Donchin, 1977, Squires et. al., 1976). Moreover, the waves are thought, at least in part, to be generated from brain regions associated with learning and memory (Okada, 1883).

This led Emanuel Donchin and his colleagues to formulate the 'context updating' hypothesis of the functional significance of the P3. This assumes that the P3 reflects the updating of working memory (Donchin & Israel, 1980; Fitzgerald & Picton, 1983; Donchin et. al., 1988). Thus relatively infrequent events elicit large P3 components because the immediate memory for the preceding target stimulus has decayed and is refreshed by the neural events that occur upon the presentation of a new target stimulus. Conversely, frequently occurring stimulus events

maintaining stronger representations in working memory do not require as much updating and therefore yield smaller P3 waveforms (Donchin, 1988). Indeed P3 amplitude also has been found to be larger for stimulus items which are remembered from previous presentations compared to similarly presented items which are not, although some evidence suggests that these effects may be modulated by an overlapping potential more directly related to memory operations than the P3 (Paller *et. al.*, 1988). Also, since the P3 occurs after the stimulus has been discriminated and categorized, the latency of its peak can be used as a measure of stimulus evaluation time (Kutas *et. al.*, 1977; Polich and Donchin, 1988) independent of response production processes (Duncan Johnson and Kopell, 1981; McCarthy and Donchin, 1981). Thus the P3 appears to reflect the fundamental cognitive operations associated with immediate memory such that its amplitude and latency vary with normal, maturational, and clinical differences in memory function (Polich, Ladish and Burns, 1990).

However, Verleger and his colleagues have proposed an alternative, 'context closure' hypothesis about the functional significance of the P3 (Verleger, 1988). This hypothesis suggests that P3s are elicited by events that are awaited when subjects deal with repetitive, highly structured tasks; P3s arise from subjects' combining successive stimuli into larger units. Thus P3 may be a physiological indicator of excess activation being released from perceptual control areas. That is, P3 indicates closure, or more precisely, deactivation of those parietal areas that control perception (Verleger *et. al.*, 1988).

In recent years there have been several studies on the role of the P3 complex, as a result of which a variety of functions for this component have been posited. According to these the P3 wave is considered to reflect cognitive resource allocation and task involvement (Kramer, Strayer, & Buckley, 1991). P3 latency is believed to reflect higher-order cognitive processes such as stimulus evaluation and categorization (Polich, 1987; Polich & Heine, 1996) and the P3 amplitude is thought to relate to the task relevance (Hillyard & Picton, 1978), probability of the eliciting stimulus (Duncan-Johnson & Donchin, 1982; Gehring, Gratto, Coles, & Donchin, 1992; Johnson, 1988) and inversely related to decision confidence (Hillyard, Squires, Bauer, & Lindsay, 1971; Ruchkin, Munson, & Sutton, 1982), decision difficulty, and stimulus discriminability (Johnson, 1986).

Summary of ERP Components

Thus, in summary, the MMN indexes the initial passive detection of a deviant auditory stimulus (Loveless, 1986), while later P2, N2, and P3 components index the allocation of the attentional resources to that novel event (Donchin et. al., 1984).

An overview of the ERP components, listing their postulated elicitation criteria as well as functional and physiological generators is provided in Table 1.3.4.

Table 1.3.4 Overview of ERP Components

ERP Wave	Time (ms)	Elicitation Criteria	Functional Generator	Physiological Generator
P1	50-100	Visual/Auditory Stimuli	Sensory Cortical Response	Primary Sensory Cortex
N1	75-150	Visual/Auditory Stimuli	Detection of Stimulus	Primary Sensory Cortex
MMN	70-300	Visual/Auditory Stimuli	Comparison of Stimulus	Secondary Sensory Cortex
P2	175-250	Perceptual/Attentional Contexts	Elaboration of Stimulus	Secondary Sensory Cortex
N2a	150-250	Perceptual/Attentional Contexts	Automatic Classification of Stimulus	Secondary Sensory Areas
N2	200-350	Perceptual/Attentional Contexts	Automatic Evaluation of Stimulus	Posterior Cortex?
P3a	250-350	Perceptual/Attentional Contexts	Orientation to Novel Stimulus	Prefrontal Cortex?
P3b	300-500	Special Attentional Contexts	Evaluation/Categorization of Stimulus	Parietal-temporal Junction?
SW	500-700	Response Requiring Contexts	Response Preparation	

1.4   Aims Of This Project

The Key Issue

It is possible that the three causal theories of dyslexia discussed earlier in this chapter are true of different dyslexic individuals. In other words, there could be three partially overlapping subtypes of dyslexia, each being an independent contribution to reading difficulties: phonological, pan-sensory and cerebellar. Alternatively, it could also be possible that just one theory accounts for every case of dyslexia, with other manifestations observed being concomitant markers. That is to say, they are associated without causation.

One important way forward would be to try and understand whether these deficits have systematic associations. The phonological deficit, a deficit at the cognitive level of processing, has been shown to be concurrent with the magnocellular deficit and also with the cerebellar deficit. Hence the questions that now arise are: what is the relationship if, any between, the two neurological deficits? Could it be possible that dyslexia is the result of one or the other neurological impairment, whereby an individual dyslexic shows only one set of deficits? Or could there be a more global cause for dyslexia of which these biological deficits are merely components, so that individual dyslexics can manifest different combinations of symptoms based upon the locus and intensity of their particular impairment?

Unfortunately, the current literature does not contain the answer to this question. Very few studies have tested dyslexics on more than one deficit, and in more than one modality. Virtually none have used electrophysiological measures to do so. This would provide the strongest possible evidence for a co-existence of the two deficits, possibly as part of a more widespread network of impairments.

Hence the next four chapters describe four experiments conducted on a set of dyslexic adolescents to answer the following essential questions: Is there a non-linguistic processing deficit in these dyslexic children? Is this processing deficit in the visual modality, auditory modality or both? Is this processing deficit perceptual, as predicted by the pan-sensory deficit theory, cognitive, as predicted by the cerebellar/automatisation deficit theory, or both? If there are indeed perceptual deficits, are these confined to the stimulus features and perceptual processing stages implicated by the visual and auditory deficit theories? If there are indeed perceptual deficits, then can these be improved by attentive practice and consequent automatisation of low-level skills, as predicted by the cerebellar/ automatization theory?

One manner in which to assess both processing stages and, by extension, both theories is using event related potentials. The sensory deficits can be assessed as changes in amplitude of the short latency exogenous waveforms, and the cognitive deficits as changes in amplitude or latency of the long latency endogenous waveforms. Furthermore, one paradigm that enables the testing of both stages of mental processing and therefore both theories is the oddball paradigm. The sensory deficits can be assessed using a passive oddball condition requiring no attention or response, and the cognitive deficits can be evaluated with an active oddball task, requiring attentive responses. In order to determine the extent to which basic processing deficits exist in the absence of linguistic processing requirements, non-linguistic visual and auditory stimuli can be used. Thus, the next four studies involve the assessment of ERP recordings to non-linguistic visual and auditory stimuli during passive and active oddball tasks in dyslexic and control adolescents.

Main Predictions for the Different Theories for Dyslexia

The predictions for this project are listed below and summarized in Table 1.5.1

Phonological Deficit

If there is a *phonological deficit* in these dyslexics, then this will be reflected by no differences in their behavioural and/ or electrophysiological responses to the non-linguistic stimuli used in these tasks.

Pan-Sensory Deficit

Visual Deficit

If there is a low level visual deficit in dyslexics as predicted by the visual theory, then this will be reflected by electrophysiological differences in the exogenous MMN component of their ERPs to peripheral field discrimination.

Auditory Deficit

If there is a low level auditory deficit in dyslexics as predicted by the visual and auditory theories respectively, then this will be reflected by electrophysiological differences in the

exogenous MMN components of their ERPs to frequency and rapid frequency sequence discrimination, but not duration discrimination.

Cerebellar Deficit

Speed of Processing

If there is a high level *speed of processing deficit* in dyslexics as predicted by the cerebellar/ automatization deficit theory, then there will be changes in the latencies of the endogenous P2, N2 and P3 wave components of the dyslexic ERPs during both visual and auditory studies and regardless of the stimulus features being manipulated in the task.

Automatization Deficit

If there is a high level automatization deficit in dyslexics as predicted by the cerebellar theory, then there will be some changes in either the amplitudes or latencies of the endogenous P2, N2 and P3 wave components of the dyslexic ERPs during both visual and auditory tasks, due to possible abnormalities in attentional mechanisms in such tasks.

Pan-Sensory AND Automatization Deficit

If there is a pan-sensory and attentional deficit in dyslexics, which is the prediction of this thesis, then the dyslexics will show all the deficits predicted by the pan-sensory and cerebellar theories described above.

Table 1.5.1.   Outline ERP Predictions For Different Dyslexia Theories on the Range of Visual and Auditory Tasks Administered

Level = Level of processing; Phon = Phonological; PSA = combined Pan-Sensory and Automatization; SOP = Speed of processing; Auto = Automatization; Amp = peak of wave; Lat = latency to peak of wave; C = cognitive; S = sensory; ⇔ = equivalent; ⇩ = significantly impaired; ⇧ =significantly improved.

Study	Level	Discrimination	Core Deficit					
			Phon	Pan-Sensory		Cerebellar		PSA
				Visual	Auditory	SOP	Auto	
			Any	MMN Amp	MMN Amp	P2 N2 P3 Lat	P2 N2 P3 Amp/Lat	Any
VS	C	Central Field	⇔	⇔	⇔	⇩	⇩	⇩
VC	S	Peripheral Field	⇔	⇩	⇔	⇔	⇔	⇩
	C	Central Field	⇔	⇔	⇔	⇩	⇩	⇩
AS	S	Easy Pitch	⇔	⇔	⇔	⇔	⇔	⇔
	S	Hard Pitch	⇔	⇔	⇩	⇔	⇔	⇩
	S	Easy Duration	⇔	⇔	· ⇔	⇔	⇔	⇔
	S	Hard Duration	⇔	⇔	⇔	⇔	⇔	⇔
	C	Easy Pitch	⇔	⇔	⇔	⇩	⇩	⇩
	C	Hard Pitch	⇔	⇔	⇔	⇩	⇩	⇩
	C	Easy Duration	⇔	⇔	⇔	⇩	⇩	⇩
	C	Hard Duration	⇔	⇔	⇔	⇩	⇩	⇩
	C	Post Practice	⇔	⇔	⇔	⇔	⇧	⇧
AC	S	Slow Speed	⇔	⇔	⇔	⇔	⇔	⇔
	S	Fast Speed	⇔	⇔	⇩	⇔	⇔	⇩
	C	Slow Speed	⇔	⇔	⇔	⇩	⇩	⇩
	C	Fast Speed	⇔	⇔	⇔	⇩	⇩	⇩

Chapter 2

Visual Processing In Dyslexia

"The most exciting phrase to hear in science, the one that heralds the most
discoveries, is not "Eureka!" but "That's funny..."

Isaac Asimov (1920 - 1992)

2.1   Study 1: Cognitive Processing of Visual Stimuli

2.1.1   <u>Introduction</u>

The following is the first study in this thesis, also called the Visual Simple (VS) study. It is also the simplest study, since it is the preliminary study, which serves as the conceptual and technical foundation upon which subsequent studies have been built.

High Level Processing Deficits in Dyslexia

To date, behavioural evidence is suggestive of underlying problems in the cognitive analysis and speed of processing among dyslexic readers (Nicolson and Fawcett, 1994). Yet while several hypotheses have been put forward regarding the nature of these deficits, the data is far from conclusive. One way in which to obtain direct information about possible differences in the nature and speed of cognitive processes in the dyslexic brain is to follow these processes using electrophysiological measures.

Impaired Speed of Processing in Non Linguistic Tasks

Section 1.2.7 of the previous chapter described several reports over the last couple of decades of deficits in rapid naming of almost all linguistic and non-linguistic stimuli in dyslexic readers. An increasing number of researchers began to view phonological processing and naming speed as separate specific sources of this disability and argued that naming speed deficits should be categorized as 'central' or cognitive processing speed deficits, and thus considered separate from phonological-based deficits for theoretical and applied reasons (Wagner *et. al..*, 1994).

Based on these observations, Marianne Wolf and Patricia Bowers proposed the 'double deficit hypothesis', which suggests that the processes underlying phonological deficits and naming-speed deficits represent two separable sources of reading dysfunction and the combined presence of both these leads to profound reading impairment (Wolf and Bowers, 1999).

Indeed, it was established by 1990 that any tasks which demands continuous speeded access to lexical information, that is, any linguistically based task, will demonstrate basic deficiencies in speed of information processing in dyslexic children. In view of the central role of information

processing speed in cognitive skills, Rod Nicolson and Angela Fawcett, the proponents of the automatization deficit theory, proceeded to focus on direct investigations of speed of processing in dyslexia (Fawcett And Nicolson, 1994).

One of the major achievements of cognitive science over the past 20 years had been the development of a procedure for administering a methodical sequence of reaction time tests, taking simpler and simpler materials, and looking for the stage at which anomalies first disappeared (Posner, 1978). Consequently, Fawcett and Nicolson ran a series of experiments using this strategy in the hope that at some point they would find a cut off where the tasks of lesser complexity would show no deficit, whereas more complex tasks would result in a deficit – that is, the point at which performance first became abnormal. If this point lay where lexical material first appeared, this would provide further strong converging evidence of a phonological deficit, whereas a continuing deficit in non lexical material would indicate that the underlying cause lay deeper. Indeed if deficits occurred right down to a simple reaction to a tone, this would suggest an underlying sensory problem.

In a study investigating the nature of the speed deficits in dyslexics, five groups of children, including two groups of dyslexics, were tested on simple reaction, selective choice reaction, and lexical decision task (Nicolson and Fawcett, 1994). In their simple reactions to a pure tone, the dyslexic children responded as quickly as their chronological age controls, and significantly faster than their reading age controls. However, in their selective choice reactions to pure tones, where only one positive response was required, the dyslexic children were significantly impaired compared with their chronological age controls, and the same as their reading age controls. Finally, in their analyses of lexical decisions to spoken words, which required an item-by-item response to words or non-words, the dyslexic children were significantly slower compared even with their reading age controls.

The pattern of results suggests that at least two factors contribute to slowness of dyslexic children: a general deficit in information processing speed, reflected in slower stimulus classification speed, and a linguistic deficit reflected in slower lexical access speed. Moreover, these deficits were observed in the same group of children who showed speed deficits in rapid automatized naming (Fawcett and Nicolson, 1994).

Deficit in Stimulus Recognition

The results are particularly intriguing: children with dyslexia appear to have a normal speed of processing in a simple reaction task, however, when a choice needs to be made, dyslexics are differentially affected by the increase in task complexity. In other words there appears to be a

progressive relative penalty for the dyslexic children as the tasks grow more and more demanding. In theoretical terms, the normal simple reaction time suggests that not only their sensory, but also their motor responses are unimpaired. Consequently, the most likely locus of the dyslexics' deficit appears to be the time needed to identify the stimulus (perceptual decision impairment). On the other hand, one might equally plausibly suggest that although the stimuli are classified just as quickly, the 'central executive' just takes longer to make the correct decision about a response (central executive impairment).

Impaired Cognitive Skill Blending

One long-term study attempted to identify the reason for this impairment, by investigating the time course of the blending of two simple reactions into a choice reaction. Two stimuli of different modalities, tone and flash, were used as well as two responses with different effectors, hand and foot, for the two stimuli, in order to avoid any problems of left-right confusions or of stimulus discriminability. Following baseline performance monitoring on simple reaction to the two stimulus separately, counterbalanced so that half the subjects had the hand button paired with the tone and foot button paired with the flash and vice versa, the two simple reaction tasks were combined into a choice reaction task in which half the stimuli were tones and half flashes, and the subject was required to press the corresponding button using the mapping established in the simple reaction tasks. The dyslexic children were no different from the controls in the simple reaction tasks, with tone or flash, hand or foot. However, by contrast, their final performances on the choice reaction task were significantly slower and less accurate than controls, and this was the case both for hand and foot responses. Moreover, the learning rates were about 1.5 times faster for controls than for dyslexics, to the extent that they were predicted to take ten times as long to learn to perform at normal levels on a task normally taking 100 hours to master. A key finding was the very poor initial performance and the continuing difficulty in eliminating errors.

Hence it was suggested that dyslexic children appeared to have greater difficulty in blending the existing skills into a new skill and their performance after practice was slower and more error prone. The researchers proposed that these children have difficulties with the initial proceduralization of any cognitive or motor skill.

One obvious way to probe the sequence of events during information processing and identify the precise cognitive stage at which this processing bottleneck occurs in dyslexics is to follow these processes using electrophysiological measures, specifically event related potentials.

ERP Indices of High-Level Deficits in Dyslexia

In recent years, a number of studies with dyslexics have reported amplitude and latency differences in both early and late endogenous ERP components in response to non-linguistic visual and auditory stimuli. In particular, delayed ERP latencies appear to be particularly characteristic of dyslexics at later stages of information processing. These findings have particular relevance to the idea of basic cognitive deficits in dyslexia, which are unrelated to linguistic processing demands.

As was discussed in a more detailed review of the P3 wave in Section 1.3.4 of Chapter 1, both the origin and functional role of the P3 are still not fully understood and remain active research frontiers. However in summary it can be said that thus P3 amplitude is controlled multiplicatively by the stimulus probability and the task relevance of eliciting events, whereas its latency depends on the duration of stimulus evaluation (Verleger, 1988). Some widely accepted interpretations of the P3 are that it is evoked by unexpected stimuli, elicited post stimulus identification and reflects completion of particular task that it is elicited for the purpose of strategic information processing, that it reflects the updating of working memory, or that its amplitude indicates the amount of processing required by a given stimulus or attention paid to a given stimulus.

Consistent findings across a number of studies indicate prolonged P3 latencies among dyslexic readers during both linguistic and non-linguistic tasks, and in both the visual and auditory modalities (Barnea, Lamm, Epstein, & Pratt, 1994; Erez & Pratt, 1992; Holcomb et. al.., 1985 and Holcomb et. al.., 1986; Harter, Anllo-Vento, Wood, & Schroeder, 1988a; Harter, Deiring, & Wood, 1988b; Johannes, Mangun, & Muente, 1994; Taylor & Keenan, 1990). Another study reported protracted N200 latencies among dyslexics in response to non-linguistic visual stimuli (symbols) (Taylor and Keenan, 1990).

One visual study examined P3 waves among dyslexic and normal children using a simple visual discrimination task. It was found that while P3 amplitude did not differ in the two groups, P3 latencies were longer among dyslexic readers (Johannes et. al., 1994). Similarly, one auditory study reported delayed N2 and P3 latencies in the selective response to auditory tones (Fawcett et. al., 1993). Another study has reported comparatively longer N140 latencies during a simple auditory recognition task and attenuated N230 latencies in a visual recognition task among language-disabled dyslexic readers (Neville, Coffey, Holcomb, and Tallal 1993). Yet another study compared auditorially presented nonsense monosyllables and pure tones among dyslexic and normal children using a target detection task and discovered longer P3 latencies in response to nonsense syllables among dyslexic readers (Erez and Pratt 1992).

Indeed most studies report either smaller P3 amplitudes and/or later P3 peaks for dyslexics, indicating a possible attentional deficit (Taylor and Keenan, 1990; Barnea *et. al.*, 1994). Furthermore this peak is less lateralized in dyslexics.

Although not all studies have yielded similar results with respect to P3 differences, there is now increasing evidence of differences in endogenous waves reflecting some differences in high level cognitive processing in dyslexia.

Aim of Study

The main aim of the study was to determine whether there were any deficits in the given set of dyslexics at higher levels of cognition, specifically, in the conscious, attentive discrimination of non-linguistic visual stimuli. This was achieved by taking physiological measurements of the brain's responses to standard and target stimuli during a selective choice reaction task. The ERP components of interest were the attention-dependent P2, N2 and P3 potentials, which index different stages of task related cognitive processing, such as stimulus evaluation, recognition, categorisation, decision-making and response selection. Both the amplitude and latency of each of these ERP components was measured to enable the assessment of cognitive capacity and resource allocation as well as the speed of processing at each stage of the cognitive sequence.

Previous investigations in this area have focussed on responses to target stimuli and provide little detail of dyslexic differences to standard stimuli. However, in this study, differences in responses to both targets and standards were examined. Furthermore, overt behavioural responses were recorded, allowing the measurement of overall performance accuracy as well as the reaction time to target stimulus events. The measurement of these factors allows a correlation of ERP component amplitudes and latencies with behavioural performance.

Hypothesis

There is a fundamental deficit at the level of cognitive processing in dyslexia, leading to differences in central resource allocation and/ or speed of processing during one or more stages of the cognitive sequence - stimulus evaluation, recognition, categorisation, decision-making or response selection. This would be reflected in these dyslexics as a difference in the amplitude or latency of one of more of the attention-dependent, task-related P2, N2 and P3 components of their event related potentials to high contrast, non-linguistic visual stimuli.

2.1.2 Methods

Subjects

The groups consisted of 14 subjects, comprising seven dyslexics and seven normally achieving controls. All the subjects were 15-year-old white males, drawn from social classes 1, 2, and 3 (middle class or skilled working class).

Subjects were recruited from the University of Sheffield's panel of dyslexic and control subjects, and had all taken part in experiments over a period of some years.

All dyslexics on this panel were previously recruited at age 7-10 from a local school for children with literacy problems, via the local Dyslexia Institute and via referral from the British Dyslexia Association helpline. Criteria for inclusion in the dyslexic panel were: discrepancy of at least 18 months between chronological and reading age; together with a full scale WISC-R/WISC III IQ (Wechsler, 1976, 1992) of at least 90 at diagnosis, without known primary neurological, emotional, behavioural or socio-economic problems, according to psychologists' reports. Standard scores for reading at diagnosis ranged from 65-92, mean 78 on the tests of single word reading (Wechsler, 1993). There was no selection criteria other than those outlined above, anybody eligible was included.

The controls on this panel were matched with the dyslexic groups overall for chronological age and IQ, had no previous history of reading difficulties, and read at worst within 6 months of their chronological age.

All of the subjects therefore had some experience in experimental procedures and were familiar with both the surroundings and the experimenter. Once they agreed to participate, all subjects were sent a confirmation letter with the time and date of the experiment along with an information sheet about the research and a consent form for requiring parental signature (see Appendix A.2.1 for further details).

Psychometric details are based on full psychometric assessments for the subjects with dyslexia, and standard short-form IQ tests (Vocabulary, Similarities, Block design and Picture completion) for the control subjects. These were obtained around 2-3 years prior to the study, because it is not good practice to retest IQ regularly.

All subjects had also been assessed for clinical evidence of ADHD in accordance with the Diagnostic and Statistical Manual of Mental Disorders 3rd edition (DSM IIIR, American Psychiatric Association, 1987). All subjects were screened for ADHD based on the parent's report and the experimenter's evaluation and the scores for each individual were then calculated (see Appendix A.2.1 for more information). A score of at least 8 out of the 14 markers of the disorder is required for clinical diagnosis. Mean scores for the groups are also shown in Table 2.1.2.a. None of the subjects showed evidence for ADHD, and there were no significant differences between the score of the two groups. Only one of the dyslexics scored 4 or more on the DSM-III R ADHD scale.

The mean reading/spelling age for each group is shown in Table 2.1.2.a, as assessed at the time they performed this experiment. It is not appropriate to report standard scores at the time of the study, because the reading tests are normed only up to age 17.

All subjects participated in each experiment with full-informed parental consent, and were paid £5 for their co-operation.

Table 2.1.2.a.   Mean Psychometric Data for Dyslexic and Control Groups

n = sample size; RA = reading age; ADHD = ADHD score

Group	n	Mean Age	Mean IQ	Mean RA	Mean ADHD
Dyslexics	7	15.52	111.43	13.18	1.85
Controls	7	15.66	120.30	17	0.50

Experimental Design

Stimulus Conditions

The images (Fig 2.1.2.a) were presented on a computer monitor situated at a fixed distance of 60 cm in front of the subjects and were all white on a black background. The interstimulus screen consisted of a fixation cross (4 x 4 mm screen size), which was a plus symbol in Helvetica font at 18 points positioned in the centre of the monitor. The target consisted of the capital letter X in Helvetica font at 144 points (3.5 x 2.9 cm screen size) and the standard consisted of the capital letter O in Helvetica font at 144 points (3.6 x 3.3 screen size). Both stimuli were presented in a predefined position, which correctly corresponded to the centre of the screen.

The stimulus presentation was based on the oddball paradigm: the infrequent target was pseudo-randomly and occasionally presented amidst the regularly occurring, frequent standard. The standard was presented for 80% trials and the target for 20%. The experiment consisted of a total of 200 trials, comprising 160 standards and 40 targets, in two blocks of 100 stimuli each. The rest between the blocks lasted for 30 seconds and was terminated by the subject pressing a key on the response pad. The practice session consisted of 10 trials, comprising 8 standard and 2 target stimuli. The stimuli appeared on the screen for 100 ms and the inter-stimulus interval (stimulus onset to stimulus onset) was 2000 ms, including a 1000 ms response wait time.

Figure 2.1.2.a Visual Stimuli Used to Elicit ERPs

(i) Ignored standard; (ii) interstimulus fixation point; (iii) attended target
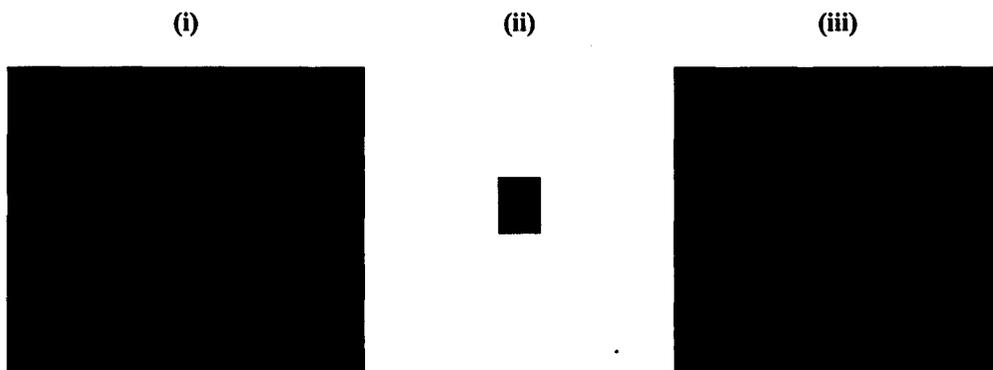
Response Conditions

The task was based on a selective choice reaction paradigm: the subjects were instructed to ignore the standard shape and attend and respond only to the target shape by pressing a key on the response pad placed in front of them. Before the experiment, a practice session comprising 10 trials was conducted with supervision, to ensure that the subjects had fully understood the procedural requirement. The subjects were told to keep their head as still as possible to avoid excessive noise artefacts during recording. During the 30-second rest period between the two blocks, they told to relax their eyes and gently rotate their head and neck if required, before resuming.

Data Acquisition

The measures used to assess the speed of information processing were the behavioural indices of reaction time and accuracy and the electrophysiological index of the ERP wave dimensions.

Behavioural Measures

The behavioural measures consisted of the subject's response time (ms) as well as their percentage accuracy. A trial was correct if the stimulus was a target and the subject responded or if the stimulus was a standard and the subject did not respond. The trial was incorrect if the stimulus was a target and the subject did not respond (omission) or the stimulus was a standard and the subject responded (commission).

EEG Recording

All electrophysiological data was obtained and processed using the Electrical Geodesics Inc stimulus presentation, data acquisition and data transformation system.

The EEG was recorded using the 65-channel dense array sensor net (65 v1 Net, Electrical Geodesics, Inc), comprising 65 electrodes embedded in yellow cellulose sponges, evenly distributed across the scalp (Tucker, 1993) (Figure 2.1.2.a). Based on the Geodesic Sensor Net sizing chart supplied by EGI, the "Adult Small" net size was used on subjects with a scalp circumference of 53.5-55 cm and the "Adult Medium" size was used on subjects with a scalp circumference of 55.5-58 cm. The net was soaked in electrolyte comprising 100 ml distilled water, 10 grams NaCl and 2 drops of baby shampoo before application on the scalp. After each use net was soaked in "Control III" disinfectant for 10 minutes and then rinsed thoroughly.

A small cross was marked at the centre point of the skull, which was calculated as the midpoint from naison to the base of the skull and then from the one ear to the other. The net was then carefully applied and the Cz electrode was placed over the centre mark. The Net Amps Diagnostics were conducted: gains were measured to ensure that 20 Hz sinusoids were visible on all channels for approximately 20 seconds, zeros were measured to ensure that the channels were quieted and decayed towards a stable baseline for approximately 40 seconds, and finally, all channels were tested to ensure that the impedance was lower than the 20 Ohm threshold. Any electrodes that had higher impedances were re-soaked in saline and then their position was readjusted to enable a lower impedance reading.

Once the subject was ready, the subject was left alone to proceed with the experiment using the Stimulus Computer in the testing room, while the EEG recordings were monitored from a separate Recording Computer in the observation room (Figure 2.1.2.b). Both computers were synchronized with a timing control box.

Figure 2.1.2.b   The Placement of the Geodesic Sensor Net on a Subject's Head
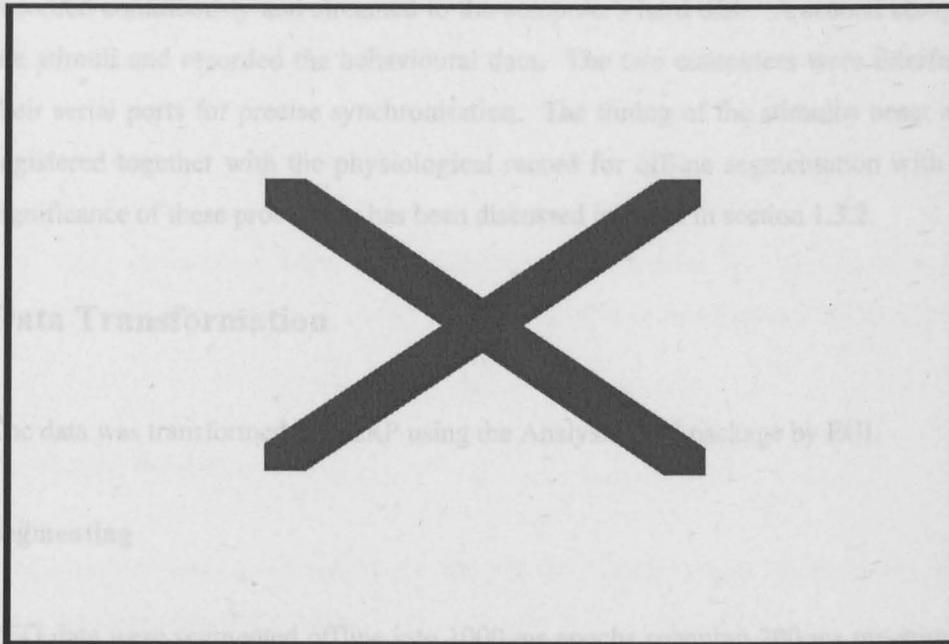
Figure 2.1.2.c   The Performance of the Visual Experiment by the Subject
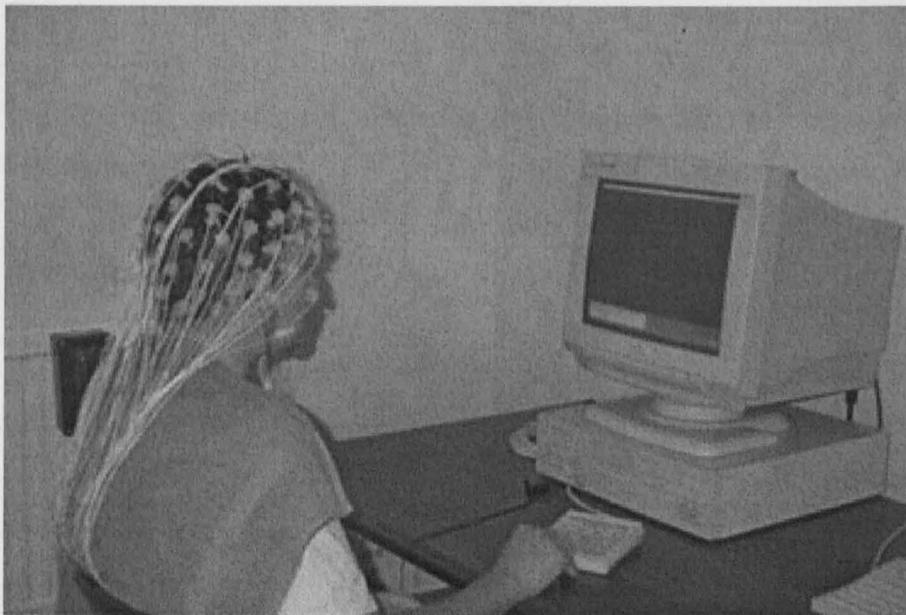
During the experiment, horizontal EEG was recorded between the electrodes nearest the external canthi and vertical EOG was recorded from supraorbital and suborbital electrodes in line with the pupil of the eye. Data were collected using the vertex electrode as a reference. The signal was amplified and filtered via a preamplifier system. The amplification was set at 1000X and filtering was done through a 0.1 Hz high-pass and 100 Hz low-pass analog filter.

The signal was multiplexed and digitized at 250 samples per second via an analog-to-digital converter positioned in an Apple Macintosh computer dedicated to data collection. Data were recorded continuously and streamed to the computer's hard disk. A second computer generated the stimuli and recorded the behavioural data. The two computers were interfaced via one of their serial ports for precise synchronisation. The timing of the stimulus onset and offset were registered together with the physiological record for offline segmentation with the data. The significance of these procedures has been discussed in detail in section 1.3.2.

Data Transformation

The data was transformed into ERP using the Analysis Tool package by EGI.

Segmenting

EEG data were segmented offline into 1000 ms epochs spanning 200 ms pre-stimulus to 800 ms post-stimulus. During segmentation, the EEG recording of one control subject was found to be truncated and could not be used.

Filtering

The EEG data were digitally filtered at 30 Hz lowpass and 10 Hz highpass to remove residual high frequency noise.

Averaging

The data were then averaged by trial type (standard and target) to create ERPs using Averager software (Electrical Geodesics Inc, Eugene, Oregon). Signals from electrode sites were marked for rejection if the weighted running average exceeded 150 mV for transit and 250 mV for voltage.

Running averages are analogous to using a band pass filter and reject both high frequency noise and low frequency drift. This method identifies the slope and rejects sharp transitions in the data. Individual sweeps during which electroocular artefact (EOG), including eye blinks and movements, occurred were also excluded. EOG activity was described as any voltage excursion exceeding 150 mV or any deviation in running averages of activity in superior eye channels exceeding 150 mV. Trials that had more than 10 electrode sites not meeting these criteria were not included in the averaging.

Replacing Bad Channels

An algorithm that derived values from the neighbouring sites by spline interpolation was used to replace data from electrodes for which more than 25% of trials were rejected by artefact.

Re-Referencing

The EEG recordings were subsequently re referenced to the linked mastoids, which corresponded to electrodes 31 and 47 in the 65 GSN Map (see Figure 2.1.2.d)

Correcting Baselines

The baselines were corrected by subtracting the average signal obtained 100 ms prestimulus, from the remainder of the trace.

Figure 2.1.2.a The 65 GSN System Superimposed on the 10-20 Electrode System
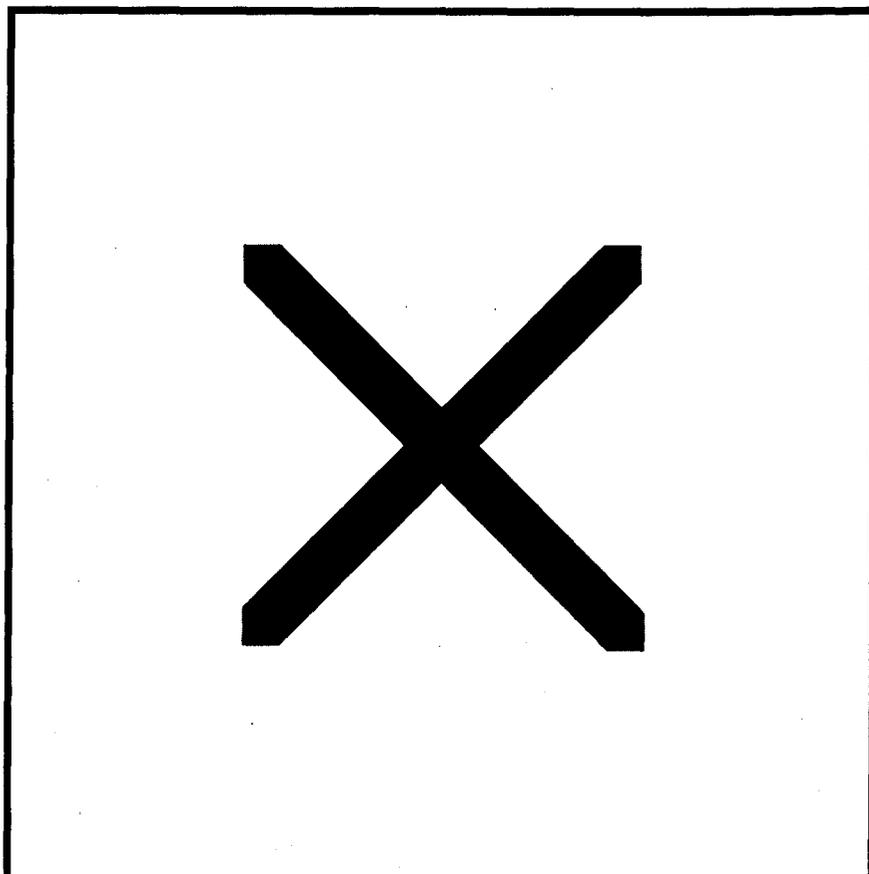
Data Analysis

ERP Wave Analysis

The averaged ERPs for each subject were averaged again to produce grand averaged waveforms for both groups. Statistical analyses were performed on the averaged ERPs for each subject. The grand averaged waveforms were used for presentation.

To reduce complexity, 10 regions of interest (ROI) were selected and data from 4-6 electrodes were averaged to produce an ERP for each ROI (see Figure 2.1.2 a). Each ROI included all GSN electrode positions closest to the equivalent single 10-20 electrode position, based on the spatial equivalence calculations by Luu and Ferree (Luu and Ferree, 2000).

These ROIs were: frontal midline (FM) comprising electrodes 3, 4, 8 and 9; anterior left (AL) comprising electrodes 10, 12, 13, 14 and 15; anterior right (AR) comprising electrodes 2, 57, 58, 61, 62; central midline (CM) comprising electrodes 5, 17, 42, 54, 65; temporal left (TL) comprising electrodes 16, 19, 20, 21, 24 and 25; temporal right (TR) comprising electrodes 46, 49, 51, 52, 53 and 56; parietal midline (PM) comprising electrodes 28, 29, 34 and 41; posterior left (PL) comprising electrodes 26, 27, 28, 32 and 33; posterior right (PR) comprising electrodes 40, 41, 44, 45 and 48; occipital midline (OM) comprising electrodes 36, 37 and 39.

ERPs to standard and target stimuli in controls and dyslexics are shown in Figure 2.1.2e. In the parietal regions, the ERPs to standards and targets are characterized by small P1 and N1 components. The response to standards returns to baseline after a brief P2. Targets evoke a larger P2, followed by an N2 and P3 component and late slow wave. These components that follow the P2 are all attenuated in the response to standards.

Temporal windows around the ERP components of interest were determined by visual inspection of the data from individual subjects, which ensured that the chosen time window captured the component of interest for all subjects. Each wave was defined in terms of being the peak positivity or negativity to standard and target stimuli at selected regions occurring in a selected latency range. These windows are listed in Table 2.1.2.

Data Extraction

For the time windows corresponding to the P2, N2, P3 and SW waves (see Table 2.1.2), the data for maximum amplitude and maximum latency to stimulus onset were extracted using MATLAB.

Figure 2.1.2.e   Grand Averaged ERPs for Controls and Dyslexics

ERPS for both groups are shown for all four midline regions. Continuous line = response to standards; Broken line = response to targets.

Frontal

Central

Parietal
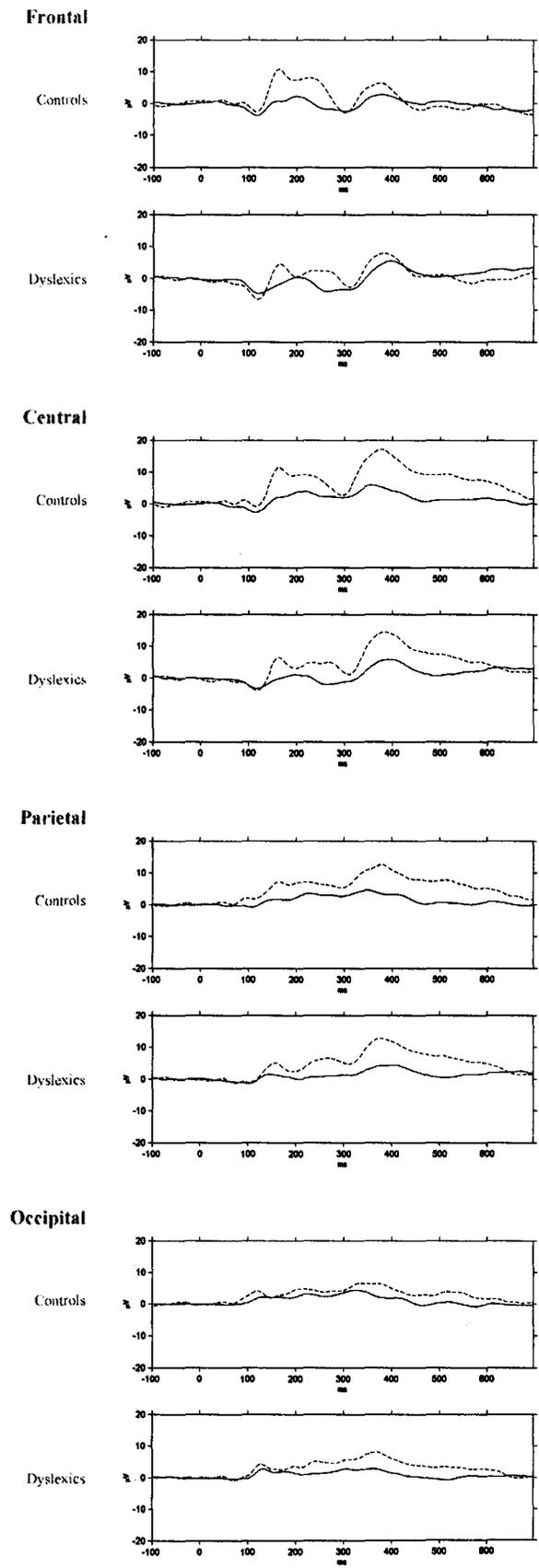
Occipital

Table 2.1.2.b   Summary of ERP Component Analysis Criteria

S = standard; T = target; F = frontal midline; C = central midline; P = parietal midline; O = occipital midline; Max Amp = amplitude of peak positivity; Max Lat = latency to peak positivity; Min Amp = amplitude of peak negativity; Min Lat = latency to peak negativity.

Waves	Stimuli	Regions	Time (ms)	Dimensions
P2	S; T	F; C; P	180-280	Max Amp; Max Lat
N2	S; T	F; C	260-360	Min Amp; Min Lat
P3	S; T	C; P; O	320-460	Max Amp; Max Lat

Statistical Analysis

These data were analysed using a 2 way repeated measured ANOVA with group (dyslexic versus control) as a between factor, and stimulus type (standard versus target) as a within-subject factor, using Sigma Stat 2.03.

Although the ERP data for all left and right regions was also analysed, these results are only included for the P3 wave, since this wave was subsequently investigated in more detail. The left and right ROI data for all the other wave components is listed in the appendix. Similarly, although time windows for the P1 and N1 waves were also defined and the data from these windows was also extracted and analysed, these results are not the focus of this study and are listed in the appendix.

2.1.3   Results

Behavioural Results

The percentage accuracy as well as the mean reaction times for control and dyslexic groups is shown in Table 2.1.3.a. The performance of dyslexics in visual target discrimination, as measured by the percentage correct responses to infrequent targets as well as frequent standards, did not differ from controls. The dyslexics were markedly slower in their responses to targets than the controls, with the group difference in mean reaction time approaching significance [$F_{(1, 13)}=3.66$, $p = 0.08$].

Table 2.1.3.a   Mean Behavioural Measures for Control and Dyslexic Groups

RT to standard not provided since it required no response.

	% Accuracy			Mean RT (ms)	
Standard		Target		Target	
Control	Dyslexic	Control	Dyslexic	Control	Dyslexic
99.29	99.12	99.64	98.93	327.20	365.07

Electrophysiological Results

The research paradigm employed in this study required the attention to, and discrimination between, two high contrast visual stimuli. Hence, these tasks elicited an early P2 component held to be associated with visual feature detection and the distribution of attentional resources as well as later N2 and P3 components held to be associated with attention and updating in working memory. All components were consistently identified regardless of the response accuracy or stimulus probability. The mean amplitude and latency measures of the various ERP waves for the dyslexic and control groups are listed in Table 2.1.3.b. All the results are summarised below, and their statistical values are provided in Table 2.1.3.c.

Table 2.1.3.b   Mean ERP Measures for Control and Dyslexic Groups

Significant group differences or interactions are highlighted; Ctrl = controls; Dys = dyslexics.

Wave	Region	Peak Amplitude (µV)				Peak Latency (ms)			
		Standards		Targets		Standards		Targets	
		Ctrl	Dys	Ctrl	Dys	Ctrl	Dys	Ctrl	Dys
P2	FM	4.30	1.66	**12.08**	**5.81**	218.86	222.86	214.86	234.86
	CM	6.88	3.07	**12.93**	**8.58**	229.71	223.43	212.00	234.86
	PM	5.20	2.75	10.38	8.26	238.86	241.14	224.57	249.71
	OM	4.64	3.07	7.08	6.26	250.86	222.29	245.71	247.43
N2	FM	-4.98	-6.28	-4.66	-3.46	309.71	282.29	307.43	317.14
	CM	-0.27	-3.89	0.66	0.06	309.14	292.57	290.29	288.57
P3	CM	8.76	6.18	19.51	15.53	**373.14**	**402.86**	379.43	385.14
	PM	6.50	4.99	13.90	13.82	366.29	365.71	384.57	376.57
	OM	5.00	3.38	7.42	8.46	351.43	352.57	365.71	361.14

P2: In dyslexics, the P2 amplitude to targets was significantly reduced at FM and CM.

N2: There were no group differences in N2 amplitude or latency to targets or standards.

P3: Although there was no group difference, the interaction between the dyslexic and control response to standard stimuli was approaching significance: post hoc analysis using the SNK test revealed that dyslexics the P3 latency to peak to standards was significantly delayed at CM.

Table 2.1.3.c   Summary of ERP Differences in Dyslexics with Inferential Statistics for Main Effects and Interactions

Diff = direction of ERP wave difference in the dyslexic group; G x S = interaction of group and stimulus; G x s = interaction of standard stimulus within group; G x t = interaction of target stimulus within group; ↓ = reduced peak to target; → = delayed peak to standard.

Wave	Region	Diff	Group (1,27)		Stim (1,27)		G x S		G x s	G x t
			F	p	F	p	F	p	p	p
P2	FM	↓	5.55	0.036	67.68	<0.001	6.30	0.027	ns	0.007
	CM		4.35	0.059	51.77	<0.001		ns	ns	0.057
P3	CM	→		ns		ns	3.38	0.09	0.042	

2.1.4 Discussion

The main findings in the present study can be summarised as follows: the P2 wave to targets was significantly **smaller** and the P3 wave to standards was significantly **later** in dyslexics.

Differences in Endogenous Waves

P2 Differences

Amplitude measures provide an index of the allocation of cognitive resources or task difficulty (Khan *et. al.*, 1999). In the present study, a decrease in the amplitude of the P2 wave in

dyslexics indicates an attenuated allocation of attentional resources for those low-level cognitive functions that are indexed by the P2 wave.

There is increasing evidence for a more endogenous role for the P2 wave. Studies of memory for visual stimuli have reported a central P2 peak that was sensitive to differences in task conditions that were equivalent on perceptual parameters (Van Petten et. al., 1991; Smith, 1993, Taylor and Smith, 1995) indicating that the amplitude of this peak is mainly related to endogenous factors. Indeed, one visual study has found that the P2 wave was larger in spatial tasks than verbal tasks, and larger in working memory tasks than in control tasks, strongly suggesting that by the time of the P2 component, the mesogenous waves begin to reflect task manipulations (Gevins et. al., 1996). However, the wave amplitude did not discriminate between matching and non-matching stimuli, which suggests that the process it represents is not involved with match detection per se. Moreover, a study with children at risk for reading difficulties found significant differences in the P2 component in two tasks that were perceptually equivalent, using words in both tasks with similar physical properties, thus providing further evidence for the endogenous functions of the P2 wave.

Recent descriptions of the functional significance of the amplitude of the P2 wave suggest that it is related to the engagement of a neural system involved with early allocating attentional or working memory resources. Therefore, a reduction in P2 amplitude in this study indicates inefficient processing of task relevant stimulus by dyslexics, particularly at the early stages of attention allocation in visual tasks. Moreover, anterior and posterior P2s are thought to index different aspects of stimulus feature detection and encoding, respectively (Dunn et. al., 1998). Reduced P2 amplitudes in both these regions in the current study suggest that dyslexics employ fewer resources in both descriptive and memory components of processing.

Various studies comparing electrophysiological responses of other developmental disorders have also found distinctive anomalies in the P2 wave. The visual P2 in dysphasic subjects was reported to be significantly enlarged compared to normal and autistic subjects in oddball studies involving omitted target events as well as targets that were stimulus changes (Courchesne and Courchesne, 1988). Conversely, reduced P2 amplitudes, such as those recorded in this study have been reported previously in children with ADHD (Halliday, 1976).

P3 Differences

Results of previous P3 visual studies are mixed with respect to the P3 differences between normal and dyslexic readers. Whereas some researchers obtained smaller P3 amplitudes to targets for dyslexics (Taylor and Keenan, 1990; Harter et. al., 1985), others could not replicate these findings (Stelmack et. al., 1988). Indeed, Duncan and colleagues found P3 abnormalities

among adults with childhood dyslexia only in those with of ADHD and proposed the differing results across groups might be due to the differences in comorbidity of ADHD in the samples of dyslexic readers (Duncan *et. al.*, 1994). The dyslexic subjects of the present study were of average intelligence and none of the subjects reported symptoms that would be suggestive of ADHD in their prior history. Thus these findings of no group differences in P3 for target stimuli in a visual oddball are in line with some of the previous research in this area.

However, the delays in the P3 wave to standard stimuli are intriguing. It is quite possible that there are in fact delays in dyslexic responses to both targets and standard stimuli but the magnitude of the effect is smaller with targets because, with only 40 target trials compared with the 160 standard trials, there are not enough of these stimuli to reveal strong group differences. This is supported by the fact that the P3 peaks to targets are noticeably delayed in dyslexics, but simply do not reach statistical significance.

It is also possible that this deficit is indeed specific to the standard stimulus. One explanation for this could be that the controls are equally prepared for the presentation of a standard or target stimulus, and simply ignore the standard once it has been classified as the irrelevant stimulus, and respond to the target once it has been classified as the relevant one. However, the dyslexics are in a greater state of readiness to recognise and respond to the relevant target, and therefore whenever the standard stimulus appears, it takes dyslexics a greater time to recognise this irrelevant stimulus and inhibit a response.

2.1.5 <u>Conclusion</u>

In accordance with the hypothesis presented at the outset, this study has revealed differences in the attention-dependent, task related P2 and P3 components indicating that the given set of dyslexics have problems with central resource allocation and speed of processing during two different stages of the cognitive sequence.

Thus this finding has established, in these dyslexics, fundamental deficits in task related attentional processing of non-linguistic visual stimuli. In contrast with the phonological deficit theory, these results strongly support the view that developmental dyslexia is not just a specific problem in language processing but also comprises deficits in other cognitive domains. Moreover, in contrast with the sensory deficit theory, the findings suggest that non-linguistic deficits in dyslexia lie in the cognitive analysis rather than just the perception of the stimuli.

2.2 Study 2: Sensory and Cognitive Processing of Visual Stimuli

2.2.1 Introduction

The following is the second study in this thesis, also called the Visual Compound (VC) study. Here, the focus of this research moves from high level to low level visual processing. The next step in this research was to ascertain whether the same dyslexics who previously demonstrated difficulties in high level cognitive processing, also demonstrated any impairments in low level perceptual processing, free of compounding problems in the attentional or higher cognitive domains. In other words, was it possible for the same set of dyslexics to have both sensory and cognitive abnormalities in the visual domain?

Despite the accumulating evidence upholding the idea of a visual deficit, a number of studies have failed to obtain corroborative data (Hayduk, Bruck, & Cavanagh, 1993; Johannes, Kussmaul, Muente, & Mangun, 1996; Greatrex & Drasdo, 1995). Such findings suggest that problems related to magnocellular functions may not be a general characteristic of dyslexia, or may characterize only a subtype of dyslexic readers (Borsting et. al.., 1996).

Low-Level Visual Deficits in Dyslexia

The three main categories of implicated visual deficits in dyslexics are those in the transient system (magnocellular), such as impaired contrast sensitivity, impaired flicker sensitivity, impaired visual persistence and impaired coherent motion detection, those in visuo-spatial attention (posterior parietal cortex), such as impaired attention focusing, attention orienting, attentional dwell time and left neglect and thirdly, peripheral processing (Stein 2000).

Impaired Peripheral Vision

Impaired peripheral vision is the processing of stimuli in the periphery and is an aspect of visual processing associated with the parietal cortex. This is often considered to be distinct from visuo-spatial attention.

In a visual task, whatever in the image is important for the performance and needs distinct processing is considered as foreground and whatever is not important is indistinct and taken as background. The distribution of foreground and background is the spatial setting of the visual strategy or task, while the visual strategy itself is a complex of many perceptual processes (ocular movement, form perception, motion perception and colour perception), which are all set for optimizing task performance. Conventionally it is supposed that an enhancing "spotlight of attention" renders more vivid what one wants to see. But the same effect is achieved by diminishing the cognitive resolution of what has lesser immediate importance. One such operation is called masking, the relegation or de-emphasising of a visual region to the background (Geiger and Lettvin, 1997).

Several studies have shown that dyslexics have difficulty masking or suppressing the information coming from the periphery of the visual field, which would interfere with the process of foveal reading (Geiger and Lettvin, 1987; Geiger, Lettvin and Fahle, 1994; Rayner, Murphy, Henderson et. al.., 1989). This could be due to a specific deficit of inhibiting stimuli outside the focus of attention (Morris and Rayner, 1991).

One specific form of masking pertains to the negative effect on the detectability, discriminability or recognition of a target by non-overlapping, spatially adjacent patterns. For instance, the recognition of a target letter is impaired if it is flanked by other letters. This observation is often explained in terms of a blurring process that spreads the contours of the flanking letters so that they mask the target letter. This phenomenon is known as 'lateral masking' in psychophysics and experimental psychology and as 'visual crowding' in ophthalmics and vision research. Masking or crowding is actively imposed, that is it is achieved by central attention. Thus, in addition to unstable visual perceptions due to unstable binocular control, it is suggested that deficits in selective attention (Flom, 1991) and visual categorisation (Huckauf et. al., 1999) may also contribute to problems with masking. Also, its distribution over the visual field is not fixed: the effect is small in foveal vision but plays a major role in the normal peripheral visual field (Leat et. al.., 1999).

Several studies have found children with reading deficits to be more vulnerable to visual masking or crowding, making more errors when letters are crowded together (Atkinson, 1991, 1993, Spinelli et. al., 2001). Moreover, visual crowding has been demonstrated for words embedded in other words but not for words presented alone. Similar results have been obtained for isolated or crowded strings of symbols, indicating a pre-linguistic deficit with the analysis of small, closely spaced visual stimuli, as in reading (Spinelli et. al., 2001).

Thus it is evident that dyslexics appear to have an abnormal distribution of peripheral field processing compared with controls. Of the three categories of visual deficits, peripheral processing lends itself well to being tested in the framework of the oddball paradigm. Moreover, the previous study involved visual discrimination using high contrast visual shapes. One legitimate argument could be that the design was not counterbalanced, and therefore these deficits could have been due to problems with perceptual integration, such as feature detection. Therefore it was important to test these dyslexics on another categorisation task using completely different stimuli. Therefore this study assessed the pre-attentive and attentive processing of the previous dyslexics using a different set of visual stimuli, during processing in the peripheral field as a marker for automatic stimulus discrimination, and processing in the central field as a marker for the attentive stimulus categorisation.

ERP Indices of Low-Level Deficits in Visual Tasks in Dyslexia

Following a decade of psychophysical research into the visual deficits in dyslexia, the focus has more recently turned to electrophysiological work, specifically evoked potentials, perhaps to secure a more objective form of evidence in support of the theory. Some abnormalities had previously been noticed in the morphology and topography of visual evoked potentials (VEP) in dyslexics, but the method became more sharply focused on the particular problem of a magnocellular or parietal deficit.

Research carried out examining various early components suggests that latencies may occur later among dyslexic readers in visual tasks. One study using visual stimuli reported a significant prolongation of the P100 wave in dyslexic children when responding to high-contrast, small-checked (high-spatial frequency) patterns (Brecelj, Strucl, & Raic, 1996). Conversely, another study found that N1 and P1 latencies of visual evoked potentials among dyslexic children were longer in response to low, but not high, spatial frequency targets (Lehmkuhle, Garzia, Turner, and Hash, 1993).

The most significant observation is the reduced amplitude and latency of the evoked response to low contrast and low spatial frequency stationary sine wave gratings (May et. al., 1991). It has also been shown that the evoked potentials to transient gratings, specifically the contrast reversal of a checkerboard pattern, is significantly different at low contrast and high temporal frequency while responses to lower frequencies and to higher contrast at all stimulating frequencies are all within normal range (Livingstone et. al., 1991, Maddock et. al., 1993, Lehmkuhle et. al., 1993). Another study in favour of both magnocellular and parvocellular deficit has found higher contrast thresholds for the activation of the magnocellular pathway in

dyslexic subjects, and suggested that there may be a similar difference in parvocellular pathway activation, though all other studies conclude there is no parvocellular deficit in dyslexics (Ridell and Hainline, 1993). However, one study failed to find any difference that might be interpreted as magnocellular deficiency (Victor et. al., 1993).

Visual Mismatch Negativity

Most auditory studies (including the auditory studies conducted in this project), which test such pre-attentional perceptual processing mechanisms, have used the auditory MMN wave of the ERP as an index for this aspect of processing. This wave is generated to an infrequent oddball, only when the subject is not attending to the stimuli. Therefore, in the interests of consistency and comparability, the most preferred index for automatic visual processing would be an equivalent visual MMN-like component elicited by a similar paradigm that is used to generate the auditory MMN.

Näätänen has argued that the automatic detection of stimulus change plays an important part in directing attention to events of biological importance (Näätänen, 2000). If this is indeed so, then one would expect a similar mechanism to operate in the visual modality. Johnston and colleagues described a novel pop out phenomenon has been described in the visual system and has been attributed to a mechanism which ensures a degree of vigilance to environmental change, enabling the noticing of unexpected events (Johnston et. al., 1993). According to their mismatch theory, soon after exposure to a visual scene, the perceptual system becomes relatively unresponsive to stimuli that match expectations. This inhibition of perceptual activity for expected stimuli yields a relative increase in sensitivity to any unexpected event in the scene. Thus, novel pop out enables an individual to rapidly detect unanticipated intrusions into their surroundings.

In the last decade a number of electrophysiological studies have, indeed, reported visual N2 components associated with stimulus change or novelty (Kenemans, et. al., 1992; Nyman, 1990; Camman, 1990; Czigier and Csibra, 1992; Woods et. al., 1992; Alho et. al., 1992; Luck and Hillyard, 1994; Prechti and Bullock, 1993). However, the possibility that these components are sensitive to attention has precluded their interpretation as the visual analogues of the auditory MMN (Näätänen, 1990). An essential property of a mechanism for detecting novel or changed stimuli is that it must operate automatically if it is to detect potentially significant events that are not the current focus of attention.

A visual analogue of the auditory MMN would thus be evoked by a stimulus change in parts of the visual field outside the focus of attention and would be generated, like the auditory MMN,

chiefly in sensory specific cortex. Specifically, it would be generated in occipital and or posterior temporal areas.

Visual MMN Evoked by Peripheral Field Processing

A recent study by Stuart Butler and his colleagues in Bristol succeeded in demonstrating a visual analogue of the auditory MMN (Tales *et. al.*, 1999). In their experiment, evoked potentials were recorded to target stimuli in the centre of the visual field, and to frequent standard and infrequent deviant stimuli presented outside the focus of attention, in the peripheral field. They found that deviants evoked a more negative potential than the standards 250-400 ms after stimulus onset. This negativity was distributed over supplementary areas of the occipital and posterior temporal cortex. Counterbalancing the stimuli produced the same effect, thereby indicating that the negativity was associated with the rarity of the deviants and not the physical features, which distinguished them from standards. This negativity was also found to share a number of characteristics with the auditory MMN.

Thus, given that processing stimuli in the peripheral field has been found to yield a visual analogue of mismatch negativity in normal subjects, and that this form of peripheral field processing is implicated in dyslexia, one would expect to find some differences in the mismatch negativity of dyslexics on this particular task.

Aim of Study

The first aim of the study was to determine whether there were any deficits in the given set of dyslexics at the lower levels of visual perception. The specific mechanism of interest was the automatic discrimination of visual stimuli outside the focus of attention. This was achieved by taking physiological measurements of the brain's responses to deviant stimuli in the peripheral field while the focus of attention was directed to the central field, allowing the peripheral field processing to be free from confounding task-related effects such as attention or cognition. The ERP component of interest was the N1 wave, which indexes the detection of transient stimulus features, and the visual analogue of the MMN potential, which indexes the accuracy of pre-attentive discrimination. This study was based on the visual MMN design used by Butler and colleagues on normal readers (Tales *et. al.*, 2000), but unlike their study, which counterbalanced the stimuli and found no difference, the current study used one set of visual stimuli.

This study also sought to determine whether there were any deficits in the given set of dyslexics at higher levels of cognition. The particular task of interest was the conscious, attentive

discrimination of non-linguistic visual stimuli. This was achieved by taking physiological measurements of the brain's responses to standard and target visual stimuli presented in the central field during a selective choice reaction task. The ERP components of interest were the attention-dependent P2, N2 and P3 potentials, which index different stages of task related cognitive processing, such as stimulus evaluation, recognition, categorisation, decision making and response selection. Both the amplitude and latency of each of these ERP components was measured to enable the assessment of cognitive capacity and resource allocation as well as the speed of processing at each stage of the cognitive sequence.

This study would also enable a comparison of any cognitive deficits in dyslexics with those found in the previous visual study using the same dyslexics.

Hypotheses

1. There is a fundamental deficit at the level of perceptual processing in dyslexics, leading to an abnormal distribution of processing in the peripheral field. This would be reflected in the dyslexics as a difference in the amplitude or area of the visual MMN component of their event related potentials to the deviants presented in the peripheral field.

2. There is a fundamental deficit at the level of cognitive processing in dyslexia, leading to differences in central resource allocation and/ or speed of processing during one or more stages of the cognitive sequence - stimulus evaluation, recognition, categorisation, decision-making or response selection. This would be reflected in these dyslexics as a difference in the amplitude or latency of one of more of the attention-dependent, task-related P2, N2 and P3 components of their event related potentials.

2.2.2 **Methods**

Subjects

The subjects were the same as those in the previous experiment (VS), with the exception of one dyslexic who had moved in the interim and could not be contacted. Thus the groups for this study consisted of 13 subjects, comprising six dyslexics and seven normally achieving controls. All subject details as well as their recruitment and assessment procedures have been described in the methods section of the previous experiment (Section 2.1.2).

Experimental Design

Stimulus Conditions

The stimuli were presented on a computer monitor situated 1 metre in front of the subjects. The inter-stimulus screen consisted of a centralized small white frame (1.3 x 1.3 cm) against a black background. The target consisted of the same centralized frame, filled completely with white. A larger white frame (10.5 x 10.5 cm) defined an area within which standard and deviant stimuli were presented. The standards consisted of single white bars (3.9 x 1.2 cm) presented simultaneously above and below the central white-framed square. The deviants consisted of double white bars equal to the standards in total area (3.9 x 0.6 X 2 cm) and brightness and presented in the same locations. All four stimuli are shown in Fig 2.2.2.a.

Figure 2.2.2.a   Visual Stimuli Used to Elicit ERPs

(i) Inter-stimulus screen; (ii) attended target; (iii) ignored standard; (iv) ignored deviant.
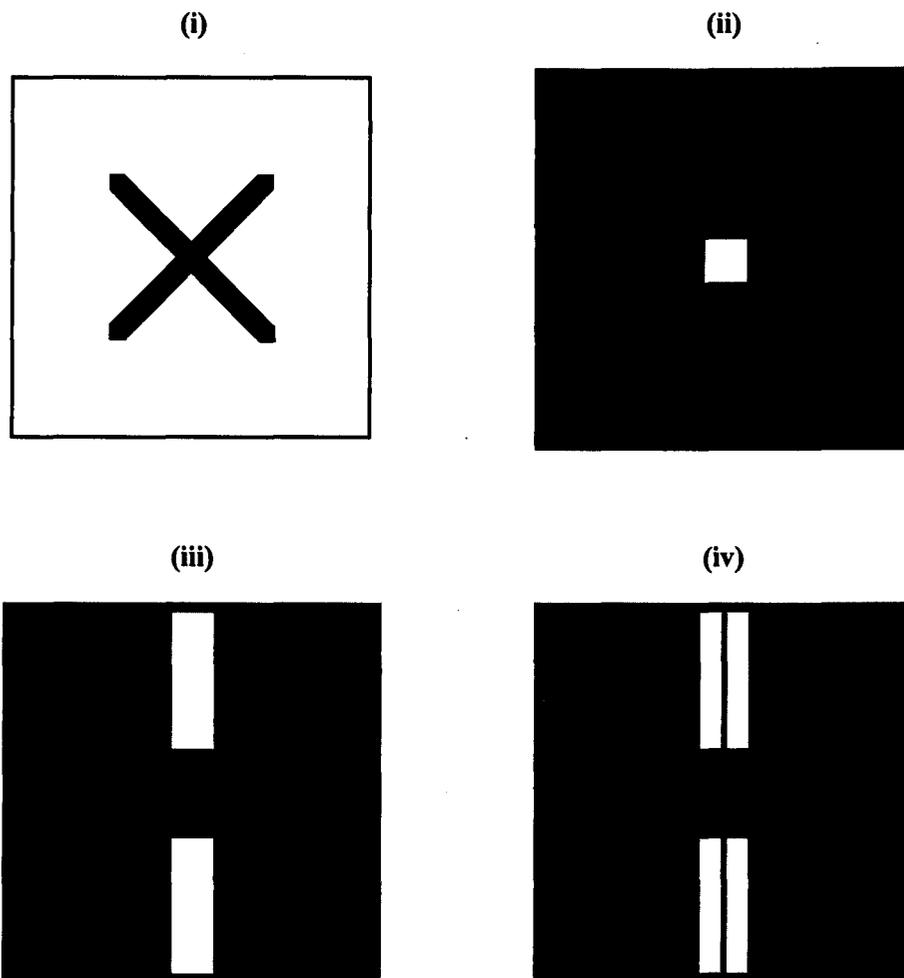
The stimulus presentation was based on the oddball paradigm: the infrequent oddball stimulus or 'target' is pseudo-randomly and occasionally presented amidst a regularly occurring, frequent stimulus or 'standard'. The standard was presented for 80% trials. However, since this experiment consisted of two oddballs, the attended oddball or target was presented 10% of trials, the non-attended oddball or deviant was presented 10% of trials. In order to have enough oddball trials for analysis, the experiment consisted of a total of 400 trials comprising 320 standards, 40 targets and 40 deviants, in four blocks of 100 stimuli each.

The stimuli appeared on the screen for 100 ms and the inter-stimulus interval (stimulus onset to stimulus onset) was 2000 ms, including a 1000 ms response wait time.

The stimulus in this experiment was of a shorter duration than in the previous visual experiment. This is because this provided a very short time frame for standard or target identification, thereby ensuring complete attention like focus on the central frame (Butler, personal communication). The numbers of trials were twice that of the previous experiment. This is because this experiment comprised two oddballs, both requiring the recommended minimum of 40 trials for the purposes of good signal averaging. Thus, the standard had to be increased to 320 in order to retain the 8:1:1 ratio thus ensuring that the target remains a rare event for which subjects would have to maintain a sharp attention like focus, and reducing the likelihood of attention to standards and deviants (Tales *et. al.*, 1999). The symmetrical location of standards and deviants about the target area was intended to minimise any tendency for attention of fixation to be biased away from the central square.

Response Conditions

The subjects were instructed to fixate and attend exclusively to the small frame at the centre of the computer monitor. The task was based on a selective choice reaction paradigm: the subjects were asked to ignore the standard (empty square) and respond only to the target (filled square) by pressing a key on the response pad placed in front of them. Before the experiment, a practice session comprising 10 trials was conducted with supervision, to ensure that the subjects had fully understood the procedural requirement.

Data Acquisition

The behavioural measures were, as in the previous experiment, response time and accuracy. The EEG was recorded using the same hardware, software and procedure as has been described in the previous experiment.

Data Transformation

Data was transformed using the same procedure and sequence as in the previous experiment, and to the same criteria and specifications.

One exception was that the data was referenced to the Fz electrode in order to enable the analysis of mismatch negativity in the occipital regions (Tales et. al., 1999). The data was also referenced to the linked mastoids for analysis of the remaining P2, N2 and P3 waves from all four regions.

Data Analysis

ERP Wave Analysis

The averaged ERPs for each subject were averaged again to produce grand averaged waveforms for both groups. These grand averaged waveforms are used for presentation below (Figure 2.2.2a and b). Statistical analyses were performed on the averaged ERPs for each subject.

To reduce complexity, 10 regions of interest (ROI) were selected and data from 4-6 electrodes were averaged to produce an ERP for each ROI. These ROIs were the same as in the previous experiment and corresponded to the same GSN electrode positions.

Figure 2.2.2.a   Grand Averaged Fz Referenced ERPs for Controls and Dyslexics

Continuous line = response to standards; Dotted line = response to deviants; Broken line = response to targets.

136
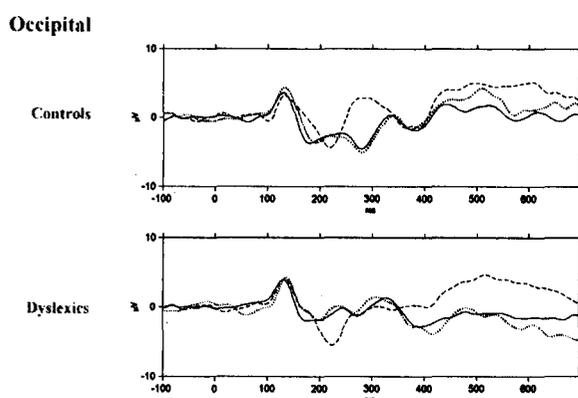
Figure 2.2.2.b   Grand Averaged Mastoid Referenced ERPs for Controls and Dyslexics

ERPS at all four midline regions are shown for both groups. Continuous line = response to standards; Broken line = response to targets.
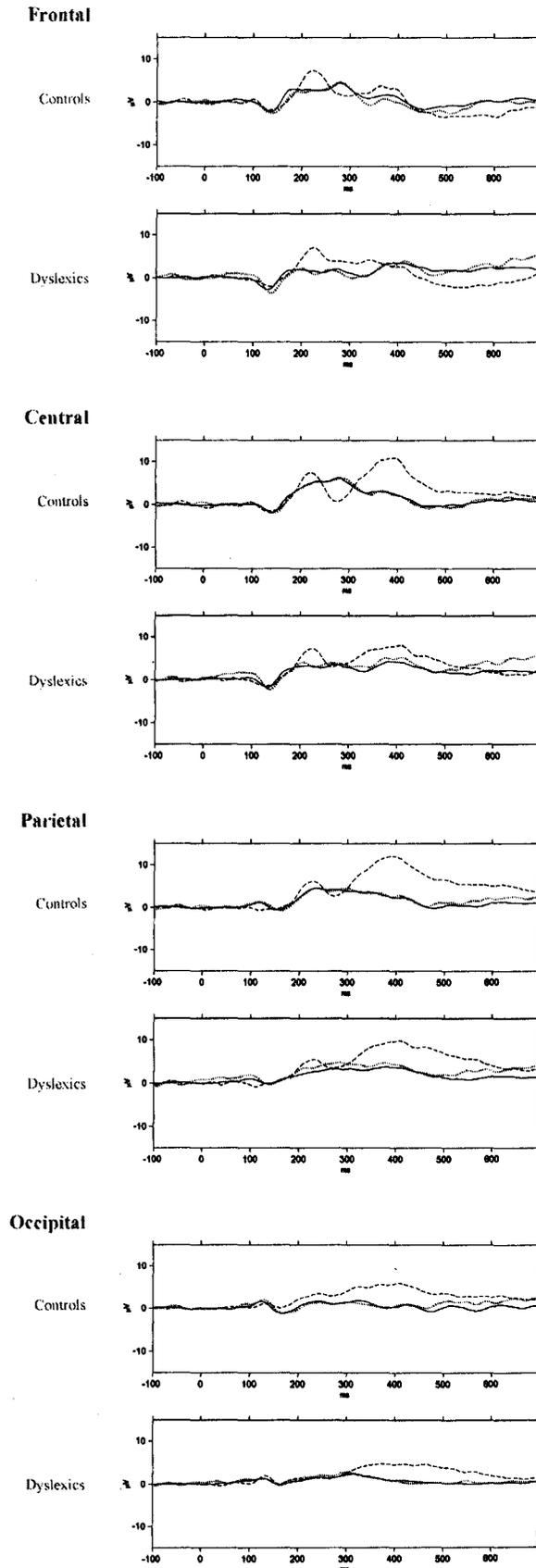
The potentials evoked by the standard, deviant and target stimuli in controls and dyslexics are shown in Figure 2.2.2.a and b. At the occipital region of the Fz referenced data (Fig 2.2.2.a), the ERPs to standards, deviants and targets are characterized by small P1 and prominent N1 components. The ERPs to standards and deviants evoke a small P2 followed by an additional negativity, after which they gradually return to baseline. Although this is not evident in the grand average trace, this negativity is larger to deviants than standards in most individual traces. The more negative response to deviants has been considered to correspond to mismatch negativity (Tales et. al., 1999). At the central and parietal sites of the mastoid referenced data (Fig 2.2.2.b) a similar though attenuated response pattern is seen, except that the targets evoke prominent P2, N2 and P3 components, which are attenuated or absent in the responses to standards and deviants.

Temporal windows around the ERP components of interest were determined by visual inspection of the data from individual subjects, which ensured that the chosen time window captured the component of interest for all subjects. Each wave was defined in terms of being the peak positivity or negativity to standard and target stimuli at selected regions occurring in a selected latency range. These windows are listed in Table 2.2.2.c. It is important to specify that this nomenclature follows the process based convention for defining ERPs, where MMN is taken as an the additional negativity immediately proceeding N1, *as well as* the wave form and anatomy based convention adopted in other studies, where MMN is taken as the attention independent equivalent of N2 (Oades and Dittman-Balcar, 1995; Alho, Woods and Algazi, 1992). This is because the deviants evoked negativities in both time windows.

Table 2.2.2.c   Summary of ERP Component Analysis Criteria

S = standard; D = deviant; T = target; F = frontal midline; C = central midline; P = parietal midline; O = occipital midline; Max Amp = amplitude of peak positivity; Max Lat = latency to peak positivity; Min Amp = amplitude of peak negativity; Min Lat = latency to peak negativity; Area = total area of negativity.

Waves	Stimuli	Regions	Time (ms)	Dimensions
N1	S; D	O	140-240	Min Amp
MMN1	S; D	O	240-320	Min Amp; Area
MMN2	S; D	O	380-460	Min Amp; Area
P2	S; T; D	C; P; O	160-260	Max Amp; Max Lat
N2	S; T; D	C; P	260-360	Min Amp; Min Lat
P3	S; T; D	C; P; O	340-420	Max Amp; Max Lat

Data Extraction

For the time window corresponding to the MMN wave, the data for peak negativity and total negative area were extracted, and for the time windows corresponding to the P2, P2 and P3 waves the data for peak positivity and latency to peak were extracted, using MATLAB.

Statistical Analysis

The MMN, P2, N2 and P3 data were analysed using a 1 way or 2 way repeated measured ANOVA with group (dyslexic versus control) as a between factor, and stimulus type (standard versus deviant for MMN and standard, target and deviant for P2, N2 and P3) as within-subject factors, using Sigma Stat 2.03. Although the ERP data for all left and right ROIs was also analysed, these results are not the focus of this study and are listed in the appendix.

2.2.3 Results

Behavioural Results

The percentage accuracy as well as the mean reaction times for control and dyslexic groups is shown in Table 2.2.3.a.

The performance of dyslexics in visual target discrimination, as measured by the percentage correct responses to infrequent targets as well as frequent standards and deviants, did not differ from controls. Although the dyslexics were markedly slower in their responses to targets than controls, this difference did not reach statistical significance.

Table 2.2.3.a   Mean Behavioural Measures for Control and Dyslexic Groups

RT to standard and deviant not provided since they both required no response.

% Accuracy						Mean RT (ms)	
Standard		Target		Deviant		Target	
Control	Dyslexic	Control	Dyslexic	Control	Dyslexic	Control	Dyslexic
99.73	99.38	99.38	99.29	99.38	100.00	364.46	403.89

Electrophysiological Results

The mean amplitude, area or latency measures of the various ERP waves for the dyslexic and control groups are listed in Table 2.2.3.b. The significant differences are provided in Table 2.2.3.c and summarized below.

Table 2.2.3.b   Mean ERP Measures for Control and Dyslexic Groups

MMN1 and MMN2 show area measures, while N1, P2, N2, P3 and SW waves show latency measures; Ctrl = controls; Dys = dyslexics.

Wave	Region	Peak Amplitude (µV)						Peak Latency (ms) or Area ((μV^2))					
		Standard		Target		Deviant		Standard		Target		Deviant	
		Ctrl	Dys	Ctrl	Dys	Ctrl	Dys	Ctrl	Dys	Ctrl	Dys	Ctrl	Dys
Non Attentive													
N1	OM	-2.04	-1.22	-0.57	-0.47	-2.35	-1.25						
MMN1	OM	-5.13	-2.21	-2.24	-4.07	-6.23	-2.23	-242.28	-28.22	142.27	-91.97	-294.19	18.96
MMN2	OM	-2.36	-3.69	-2.10	-0.77	-2.56	-5.14	22.98	-176.38	130.85	82.61	65.18	-234.26
Attentive													
P2	FM	5.25	4.50	9.20	7.12	5.24	4.45	208.50	201.14	227.50	225.71	104.75	101.00
	CM	6.54	5.39	8.55	7.72	6.64	5.58	229.50	216.00	221.50	222.29	108.38	103.71
	PM	5.17	3.69	6.68	5.69	5.25	5.12	229.00	229.71	226.00	226.29	108.50	107.71
	OM	2.48	2.19	4.60	2.28	2.36	2.68	226.00	216.57	230.00	210.29	107.50	105.43
N2	FM	0.13	-0.21	-0.98	1.54	-2.21	-1.03	326.50	311.43	310.50	306.86	326.50	313.71
	CM	1.94	1.62	-0.72	2.05	1.29	1.66	311.00	313.14	284.00	290.86	328.00	296.57
P3	CM	3.61	4.78	12.50	9.14	4.00	6.75	374.00	389.14	386.00	389.71	144.38	146.71
	PM	4.14	4.04	12.96	10.52	4.79	5.54	350.00	369.71	390.50	399.43	144.25	144.14
	OM	2.17	2.01	6.84	5.23	1.87	2.12	360.00	344.57	391.00	389.71	144.88	139.57

N1: There were no significant group differences in N1 amplitude to deviants or standards.

MMN1: There were no significant group differences in MMN amplitude or area to deviants.

MMN2: Although there were no group differences, there was a significant interaction between the dyslexic and control response to deviant stimuli: in dyslexics, the MMN2 area was significantly greater at OM

P2: Although there were no group differences, there was a significant interaction between the dyslexic and control response to target stimuli: in dyslexics the P2 amplitude to targets was significantly reduced at OM.

N2: There were no significant group differences in N1 amplitude or latency to targets, deviants or standards.

P3: Although there was no group difference, there was a significant interaction between the dyslexic and control response to target stimuli: in dyslexics the P3 latency to standards was significantly delayed at PM.

Table 2.2.3.c   Summary of ERP Differences in Dyslexics with Inferential Statistics for Main Effects and Interactions

Diff = direction of ERP wave difference in the dyslexic group; G x S = interaction of group and stimulus; G x s = interaction of standard stimulus within group; G x t = interaction of target stimulus within group; _ = increased area under response to deviant; ↓ = reduced peak to target; → = delayed peak to standard.

Wave	Region	Diff	Group (1,44)		Stim (1,44)		G x S		G x s	G x d/t
			F	p	F	p	F	p	p	p
MMN2	OM	_	6.24	0.027						0.030
P2	OM	↓			5.83	0.008	7.93	0.002		0.049
P3	PM	→	4.42	0.055	975.6	<0.001			0.025	

2.2.4 <u>Discussion</u>

The main findings of interest in the present study can be summarised as follows: in the passive aspect of the task, the MMN amplitude was significantly **larger** in the dyslexics. In the active aspect of the same task, the P2 to targets was significantly **smaller** and the P3 to **standards** was significantly later in dyslexics.

Differences in Exogenous Waves

MMN Differences

The data suggests that subjects successfully maintained fixation and attention on the target area and ignored the standards and deviants because P3 is present in the responses to targets, but absent in the responses to both standards and deviants. If deviant and standard stimuli were indeed outside the focus of attention, the greater negativity of the response to deviants in the control subjects must reflect the operation or pre-attentional, automatic processing. In other words, the additional negativity may be the visual equivalent of the auditory MMN, as demonstrated in the previous paper by Butler and colleagues. This MMN is significantly enhanced in dyslexics, suggesting abnormal automatic, non- attentive discrimination in the peripheral visual field.

Impaired Peripheral Vision

The dyslexics were able to discriminate in the vertical peripheral field to a greater degree than controls. This is consistent with previous studies of the horizontal peripheral field, which have demonstrated the dyslexics have significant differences in lateral masking or visual crowding. Masking can be measured by the form resolving field measure (FRFM), which is the accuracy of recognition of peripheral stimuli as a function of distance from the centre of gaze. This measure of peripheral vision in dyslexics is found to differ significantly from that of normal readers in a study comparing dyslexic and normal readers with respect to how well they identified letters and short strings of letters briefly presented in the peripheral visual field at the same time that a single letter was presented at the fixation point of gaze (Geiger and Lettvin, 1987). Specifically, their recognition of the letter pair when the peripheral letter is nearest to the center on the right is worse than when the peripheral letter is further away in the periphery, whereas in normal readers best recognition of a letter pair is when the peripheral letter is nearest to the center; and recognition falls off rapidly as letters are further away. Also recognition of the peripheral letter farther in the periphery in the direction of reading is significantly better than on the other side and significantly better than that of ordinary readers. Thus adult dyslexics and adult ordinary readers significantly differ in the distribution of lateral masking as measured by their FRFM (Geiger and Lettvin, 1997).

Demonstration of Visual MMN

There are several reasons why this negativity, which is attenuated in dyslexic compared with controls, can indeed, be assumed to be the analogue of the auditory MMN.

Firstly, Alho has argued that if a visual MMN exists its elicitation may have a higher threshold than auditory MMN, which is evoked by any discriminable change. The stimuli used in this experiment were easily discriminable in the peripheral field. Secondly, source location techniques applied to electrical and magnetic ERPs and also recordings from the surface of the temporal lobe have shown that the generators of auditory mismatch negativity are situated in temporal association cortex anterior to the primary auditory projection area. The negativity associated with deviants in the present study was maximal in the occipital regions, suggesting that its generators are, indeed, analogously located in supplementary visual areas.

However, although the stimuli used as deviants and standards were equated for area and brightness, the deviants were spatially more complex: their contours were of greater total length and the figures were divided in two. It is therefore possible that the negativity associated with deviants was the result of additional processing of the more complex figure and not the action of a mismatch detection mechanism. Even if this were the case, this additional processing is still significantly reduced in dyslexics, and still suggests deficits in peripheral processing per se.

Differences in Endogenous Waves

P2 Differences

The P2 amplitude difference in dyslexics is similar to that obtained in the previous visual experiment. This consistent P2 amplitude reduction in two visual tasks with stimuli differing in their physical characteristics is consistent with the argument that this mesogenous wave represents processes that are related to task, rather than stimulus, attributes. Thus, the differences in both visual studies might be viewed as evidence of a general visual deficit in feature-independent higher perceptual processes that have some attentional or memory requirements.

However, the discussion of the P2 wave in some past studies has emphasized the exogenous properties of this peak, including its involvement in the processing of perceptual features (Stelmack and Miles, 1990), early sensory stages of encoding (Dunn et. al.., 1998) and selective attention (Hackley, Woldorff, & Hillyard, 1990). If such is the case, it is possible that a top down processing effect may contribute to the P2 abnormalities: if some higher component of the attentional task, such as stimulus categorisation, is not fully automatized in dyslexics, then the available resources required to perform other basic attentional or encoding components of the task are likely to be scarce, and this could be reflected in the attenuation of the P2 wave.

It is important to note that the difference in latency was specific to the right central region. This laterality difference is consistent with previous reports of a right parietal deficit in dyslexics. Although this deficit is demonstrated as left neglect, it is possible that it results in impairments in other attentional mechanisms required in such tasks.

The delay in the P3 wave to standard stimuli is similar to that obtained in the previous visual experiment. The P2 amplitude difference in dyslexics is similar to that obtained in the previous visual experiment. This consistent P3 difference in two different visual tasks is consistent with the argument dyslexics have difficulties in processing mechanisms that pertain to task, rather than stimulus, attributes. Some of the possible explanations for this difference were discussed in that previous chapter. However, since there is very little literature on the functional significance of the P3 response to the frequent and expected standard stimulus, it is difficult to speculate too much on the possible implications of these results, except to suggest that this finding provides further evidence of abnormalities in the central processes allocated to and associated with the classification and recognition of the standard and target stimuli.

2.2.4 <u>Conclusion</u>

1. In accordance with hypothesis 1, this study has identified for one of the first times in dyslexics, a difference in the visual MMN component associated with the automatic discrimination of deviants outside the visual field of focus, indicating abnormalities in the distribution of automatic, pre-attentional processing in the peripheral field.

2. In accordance with hypothesis 2, this study has also revealed differences in the attention dependent, task-related P2 and P3 components, indicating that the given set of dyslexics have problems with central resource allocation or speed of processing during two different stages of the cognitive sequence.

Thus, these findings have established the co-occurrence of feature-specific perceptual deficits as well as general task-related cognitive deficits in the visual modality in dyslexia. These results strongly support the view that developmental dyslexia is a multi-level deficit with both low-level and high-level impairments in visual processing.

Chapter 3

Auditory Processing In Dyslexia

"If a man will begin in certainties he shall end in doubts; but if he will be content
to begin in doubts he shall end in certainties."

Sir Francis Bacon (1561 – 1626)

3.1 Study 3: Sensory and Cognitive Processing of Auditory Pitch and Duration

3.1.1 Introduction

The following is the third study in this thesis, also called the Auditory Simple (AS) study. Here, the focus of this research moves from the visual to the auditory domain. The next stage of the research was concerned with ascertaining whether these dyslexics who have been shown to have both low-level and high level visual processing impairments, also showed problems with low and high level auditory processing. In other words, was it possible for this set of dyslexics to have sensory and cognitive abnormalities in both visual and auditory domains?

Low-Level Auditory Deficits in Dyslexia

The idea that there may be a low-level perceptual basis for phonological deficits in dyslexia was first explored by Tallal and Piercy in a series of pioneering studies. They discovered impaired discrimination of rapid auditory sequences in language-impaired children. Since then studies have reported of rapid sequential speech, of transient sounds or sound patterns and of the spectral features of sounds. Of these, the best attested auditory psychophysical deficit in dyslexics is impaired *auditory frequency discrimination* (France et. al., 2002). The nature of this deficit has already been described in Section 1.2.5 of Chapter 1. In summary, several studies have found that although dyslexics had no impairments detecting the temporal features of the stimulus, accomplished by neuronal discharges at stimulus onset and offset, they were impaired in their ability to code or decode the fine spectral features, accomplished by neuronal discharges that are phase locked with the stimulus. Deweidrt and colleagues originally observed that children who read poorly also showed reduced auditory frequency discrimination. McAnally and Stein as well as Hari found elevated, just noticeable differences for auditory frequency in adults dyslexics. Ahissar and colleagues made similar observations on adults with a history of reading difficulties in childhood.

Therefore this could be considered a reliable and robust marker for possible low-level auditory deficits, and is the focus of this study.

ERP Indices of Low-Level Deficits in Auditory Tasks in Dyslexia

Impaired Frequency Discrimination

Impaired auditory frequency discrimination is one of the best-attested auditory psychophysical deficits in dyslexics. Therefore, more recently, attention has turned to electrophysiological responses associated with this impairment to secure more direct and objective forms of evidence in support of the theory and several studies have demonstrated abnormal electrophysiological responses in dyslexics.

In their study on auditory temporal coding discussed earlier, McAnally and Stein also recorded the far field potential (FFR) evoked by low frequency tones in dyslexics (McAnally and Stein, 1996). This results from the synchronous discharge of phase locked neurons and it is therefore an objective and direct measure of phase locking in the brain stem. They found that the FFR was smaller in amplitude compared to the controls, indicating a reduced synchrony of neuronal discharge due to less precise phase locking, however the average FFR latency did not differ between dyslexics and controls, confirming that the FFR was generated in the brain stem and that the recordings were not confounded by electromagnetic artefact or cochlear microphonic potentials, because the latter have shorter latencies. The click-evoked auditory brainstem response (ABR) was also recorded. This reflects the synchrony of neural discharge in response to stimulus onset. They found that the ABR amplitudes and latencies were not significantly different, suggesting that their neural coding of stimulus onsets and offsets is normal. Hence dyslexics seemed impaired only no their ability to generate or exploit neural discharges which are phase locked to the fine structure of acoustic stimuli.

MMN as an Index of Impaired Frequency Discrimination

Torsten Baldeweg and colleagues investigated these psychophysical findings using electrophysiological measures, specifically ERPs (Baldeweg, 1999). The MMN responses to graded changes in tone frequency and tone duration were recorded to assess the automatic processing of spectral and temporal features of an auditory deviant. Differences between dyslexic and control subjects were found in the MMN to frequency deviants but not to tone duration deviants, reflecting impaired frequency detection but intact coding of stimulus envelope respectively. This was consistent with the findings of McAnally and Stein. The N1 wave latency to both frequency and duration deviants, in contrast, was not different, and since this wave is only sensitive to stimulus onset and offset, again, this reflected intact detection of the stimulus envelope (Baldeweg, 1999).

Other studies have also used similar frequency deviants with dyslexics. While, one such study reported a larger frequency MMN in dyslexic school children compared to controls (Hugdahl et. al.., 1998), another study obtained attenuated MMNs to phoneme deviants, but no such differences in the MMNs to frequency deviants in dyslexics (Schulte-Körne et. al.., 1998). A subsequent study using larger frequency deviance found that the late MMN to phonemes was attenuated, but there was no difference in MMNs to frequency (Schulte-Körne et. al.., 2001).

Another study however found no deficit in frequency discrimination in dyslexics (Hill et. al., 1999). However, this study used multiple exposures per trial to the standard stimulus, unlike preceding paradigms. In an attempt to investigate whether this paradigm affected frequency discrimination in dyslexics another recent study compared a traditional two interval same-different paradigm and a variant paradigm with six intervals and found that dyslexics had larger differences in deviant stimulus detection than did controls in the two interval paradigm only (France et. al., 2000). They suggested that the discrepant results reported earlier could be due to the fact that dyslexics are known to have short auditory digit spans, and so these deficits in auditory memory could have made the one standard procedure more difficult, whereas repeated exposure to the identical standard might have counteracted such deficits and improved the dyslexic's frequency discrimination.

One interesting finding in the study was that dyslexic and control JNDs were equal at shorter ISIs, that is, there was no difference in the difference threshold at which two pitches could be judged as different. However, dyslexics became worse than controls at longer ISIs. The signal detection model of perceptual resolution distinguishes three types of psychophysical variance: sensory, which represents the unavoidable internal noise in the processing of an individual stimulus; trace variance, which represents the variability in memory processes and increases with the time between successive stimuli presented for comparison in a discrimination trial; and context variance, another memory component which arises only when the set of experimental stimuli is sufficiently small that subjects can effectively label individual items. Signal detection analysis was conducted on the findings and this suggested that both sensory variance and trace variance in dyslexics was larger than in controls.

ERP Indices of Low-Level Auditory Plasticity

Several animal and human studies in the last decade have demonstrated changes in the sensory representations in the brain following practice or training. In one of the earliest of these studies by Merzenich and colleagues, primates were trained for several weeks to discriminate small differences in the frequency of sequentially presented tonal stimuli (Recanzon et. al., 1993).

The monkeys showed a progressive improvement in performance with training compared with control monkeys and monkeys that received the same auditory stimuli but that were engaged in a tactile discrimination task. The tonotopic organisation, which is the organisation topology of the auditory cortex based on frequencies, was assessed at the end of the training period by recording multiple-unit responses at numerous cortical locations. It was found that the cortical representation, sharpness of tuning and the latency of the response were greater for the behaviourally relevant frequencies of trained monkeys when compared to the same frequencies of control monkeys. These results demonstrated that attended natural stimulation can modify the tonotopic organization of auditory cortex in the adult primate, and that this alteration is correlated with changes in perceptual acuity.

Studies have since shown that event related potentials can be used as a measure of similar plastic changes in the human auditory cortex. In one study, no MMN was initially elicited by subtle changes in a complex unfamiliar sound at the beginning of the session, but was then elicited later during the session (Naatanen et. al., 1993). The emergence of MMN during the course of the same session suggests that the representation of the standard stimulus eventually becomes precise enough to enable the cortical change detector mechanism to detect a slightly different stimulus. In other words, the result reflects a gradual sharpening of the sensory information encoded in the memory trace. Another recent study established the dynamic nature of the cortical memory representations for phonemes in adults using mismatch negativity (Winkler et. al., 1999). It was found that the MMN for a contrast between two Finnish phonemes was elicited in fluent Finnish speakers but not elicited in those with no knowledge of the Finnish language. The results suggested that the fluent Hungarians had developed cortical memory representations for the Finnish phoneme system that enabled them to discriminate the phonemes specific to the language, even at a preattentive perceptual level.

Other studies have demonstrated that mismatch negativity can be used as a measure of the plasticity of memory representations in auditory cortex induced by successful discrimination practice or training (Kraus et. al., 1995; Elbert et. al., 1995; Ahissar et. al., 1992). In all these studies, no MMN was initially elicited by subtle changes in sound that subjects were unable to discriminate. However, after discrimination training the MMN emerged in those subjects who learned to discriminate the stimulus changes behaviourally.

These training induced neurophysiological improvements have also been measured in other components of the ERP trace, which index other aspects of low-level auditory function. In one study auditory evoked potentials N1 and P2 were obtained from normal hearing adults in response to two synthetic speech variants of a syllable /ba/ (Tremblay et. al., 2001). It was found that after the subjects had learned to differentiate between the two stimuli through

training, there was an increase in the N1-P2 peak. This suggests that as perception improved with training, the amplitude of the exogenous P1 and N1 components also increased.

Other studies have reported training associated changes in neural activity that even precede behavioural learning (Tremblay, Kraus and McGee, 1998). These findings suggest that speech sound learning occurs at a pre-attentive level that can be measured neurophysiological in the absence of a behavioural response to assess the efficacy of training.

Aim of Study

The first aim of the study was to determine whether there were any deficits in the given set of dyslexics at the lower levels of auditory perception. The specific mechanism of interest was the automatic, pre-attentive discrimination of the frequency and duration of auditory tones. This was achieved by taking physiological measurements of the brain's responses to deviant and standard stimuli during a response-free condition, devoid of potentially confounding task-related effects such as attention or cognition. The ERP components of interest were the N1 wave, which indexes the detection of transient stimulus features, and the MMN potential, which indexes the accuracy of pre-attentive discrimination. This study was similar in design to that of Baldeweg and colleagues (Baldeweg et. al., 1999) but unlike their study, which used graded changes in tone frequency and duration, the current study used only one distinct and one subtle change in tone frequency and duration to allow time for two additional conditions.

This study also sought to examine whether there were any deficits in the given set of dyslexics at higher levels of cognition. The particular task of interest was the conscious, attentive discrimination of the same auditory stimuli used in the previous condition. This was achieved by taking physiological measurements of the brain's responses to the standard and targets stimuli during a selective choice reaction task. The ERP components of interest were the attention-dependent P2, N2 and P3 potentials, which index different stages of task related cognitive processing, such as stimulus evaluation, recognition, categorisation, decision-making and response selection. Both the amplitude and latency of each of these ERP components was measured to enable the assessment of cognitive capacity and resource allocation as well as the speed of processing at each stage of the cognitive sequence. Although previous research by Baldeweg and colleagues included a subsequent selective choice reaction task with the same set of stimuli, only the performance data was recorded in this condition (Baldeweg et. al., 1999). However the current study hoped to gain further insight into the precise nature and locus of any cognitive impairment by recording ERPs during the response condition.

If the frequency discrimination was indeed impaired in the first condition then the final objective of this study was to investigate whether any practice or training related changes were possible in dyslexics at the level of auditory perception, specifically, in the automatic, pre-attentive discrimination of auditory frequency. This was achieved by taking physiological measurements of the MMN potentials during a repeated unattended condition following the response based frequency discrimination task. This would enable the assessment of cortical plasticity or learning related changes in neural activity, reflected in changes in the morphology of the MMN potential.

This study would also enable a comparison of any cognitive deficits in dyslexics with those found in the previous visual and auditory studies using the same dyslexics.

Hypotheses

1. There is a fundamental deficit at the level of perceptual processing in dyslexics, leading to impairments in the automatic, pre-attentive discrimination of auditory frequency. This would be reflected in the dyslexics as differences in the amplitude or area of the MMN component to subtle changes in tone frequency but not tone duration, reflecting impaired frequency detection but intact coding of stimulus envelope respectively. The latency of the N1 component to both frequency and duration changes would not be different because this wave reflects intact detection of stimulus onset and offset.

2. There is a fundamental deficit at the level of cognitive processing in dyslexia, leading to differences in central resource allocation and/ or speed of processing during one or more stages of the cognitive sequence - stimulus evaluation, recognition, categorisation, decision-making or response selection. This would be reflected in these dyslexics as a difference in the amplitude or latency of one of more of the attention-dependent, task-related P2, N2 and P3 components of their event related potentials.

3. If there were indeed a deficit in the automatic, pre-attentive discrimination of auditory frequency, then there will be practice-induced improvements in auditory perception, leading to an enhanced ability to discriminate frequency in the repeat unattended or "familiarized" condition following the attended, response-based frequency discrimination task. This would be reflected in dyslexics as an attenuation or absence of any previous abnormalities in the MMN component to subtle changes in tone frequency.

3.1.2 <u>Methods</u>

Subjects

The subjects were the same as those in the previous experiment (AS). All subject details as well as their recruitment and assessment procedures have been described in the methods section (Section 2.1.2) of Chapter 2.

Experimental Design

Stimulus Conditions

The stimuli were pure auditory tones of 75 dB intensity presented binaurally via inner ear headphones. There were four stimulus conditions in each of which the target was an easy (1200 Hz) or hard (1025 Hz) deviation in the pitch, and an easy (250 ms) or hard (75 ms) deviation in the duration of the same single-tone standard of 1000 Hz frequency and 50 ms duration (including 5 ms rise and fall times) (Table 3.1.2.a).

The stimulus presentation was based on the oddball paradigm: the infrequent target was pseudo-randomly and occasionally presented amidst the regularly occurring, frequent standard. The standard was presented for 85% trials and the target for 15%. This percentage, though lower than that recommended for and used in the active oddball tasks, is the recommended percentage of deviants for passive oddball tasks, which enables the elicitation of more robust MMN waves (Näätänen, 1992).

In the passive and active response conditions, the experiment comprised four blocks, one for each stimulus condition. Each block consisted of 200 stimuli, comprising 170 standards and 30 targets. Thus, in total the experiment consisted of a total of 800 trials, comprising 680 standards and 120 targets. However, in the familiarized response condition, to minimise familiarity with the design and task requirements after the preceding attentive response and to ensure that any electrophysiological response to these deviants was a result of their automatic, non-attentive discrimination, rather than any expectation or attention effects, the design of this condition was changed so that the hard deviants were included with the easy deviants. Thus, in the this response condition, the first two stimulus conditions were collapsed into one block, which consisted of 400 stimuli, comprising 340 standards, 30 easy pitch deviants and 30 hard pitch

deviants presented in pseudo random order, and the third and fourth stimulus condition were also collapsed into a second block, which consisted of 400 stimuli, comprising 340 standards, 30 easy duration deviants and 30 hard duration deviants presented in pseudo random order.

In the passive and familiarized response conditions, the stimuli were delivered at a constant inter-stimulus interval of 1200 ms (onset to onset) whereas in the active response conditions the same stimulus sequence was delivered at a constant inter-stimulus interval of 2000 ms (onset to onset) including a 950 ms response wait time.

Table 3.1.2.a   Summary of Stimulus Conditions

ISI = Inter-stimulus interval; Std = standard stimulus; Tar = target stimulus.

Feature	Block	Frequency (Hz)		Duration (ms)		ISI (ms)	
		Std	Tar	Std	Tar	Passive	Active
Pitch	Easy	1000	1200	50	50	1000	2000
	Hard	1000	1025	50	50	1000	2000
Duration	Easy	1000	1000	50	250	1000	2000
	Hard	1000	1000	50	75	1000	2000

Response Conditions

Passive Condition

In order to minimise attention to the auditory stimuli, the subjects were seated in front of a television screen and instructed to watch the videotaped silent movie and ignore all other events. To ensure that full attention was paid to the movie, they were informed that they would be tested on its contents afterwards.

Active Condition

The subjects were seated in front of a computer screen and instructed to visually fixate on a small centralized cross on the computer monitor while attending to the sounds presented through the earphones. The task was based on a selective choice reaction paradigm: the subjects were instructed to ignore the standard tones and attend and respond only to the target tones by pressing a key on the response pad placed in front of them. Before the experiment, a practice session comprising 10 trials was conducted with supervision, to ensure that the subjects had fully understood the procedural requirement.

Familiarized Condition

This condition was the same as the previous passive condition, except that a different videotaped film was shown to the subjects. Since this session immediately followed the active session, which could be considered equivalent to an attentive practice, the comparison of the results of this session with those of the initial passive condition enables the assessment of any changes in automatic stimulus detection due to practice or learning (Table 3.1.2.b).

Table 3.1.2.b   Summary of Response Conditions

Response Condition	Requirements	Mechanisms Involved
Passive	No Attention, No Response	Pre-attentional; Perceptual
Active	Attentive Response	Attentional; Cognitive
Familiarized	No Attention, No Response	Post-practice Perceptual

Data Acquisition

The behavioural measures were, as in previous experiments, response time and accuracy. The EEG was recorded using the same hardware, software and procedure as has been described in previous experiments.

Data Transformation

Data was transformed using the same procedure and sequence as in previous experiments, and to the same criteria and specifications.

Data Analysis

ERP Wave Analysis

The averaged ERPs for each subject were averaged again to produce grand averaged waveforms for both groups. These grand averaged waveforms are used for presented below (Figure 3.1.2). Statistical analyses were performed on the averaged ERPs for each subject.

To reduce complexity, 10 regions of interest (ROI) were selected and data from 4-6 electrodes were averaged to produce an ERP for each ROI (see Figure 2.1.2 a). These ROIs were the same as in previous experiments and corresponded to the same GSN electrode positions.

[1]**Figure 3.1.2.a   Grand Averaged ERPs for Both Groups in the Passive Condition**

ERPS for all stimulus conditions are shown in the FM region; Continuous line = response to standards, dashed line = response to hard deviants, and dotted line = response to easy deviants.

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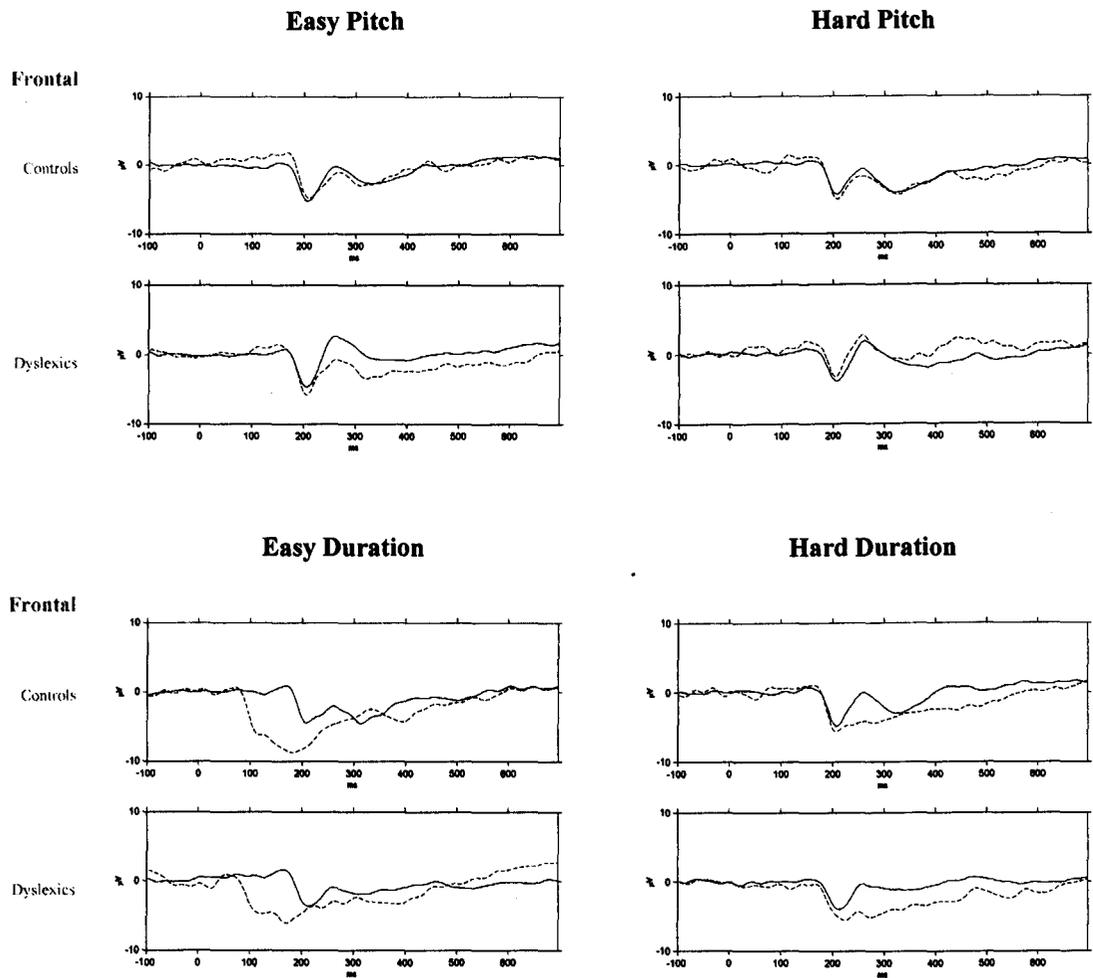
[1] In both of the auditory studies, ERPs to stimuli shorter than ~100 ms duration appear to be delayed by 100 ms. In this study this effect is seen in the passive and active ERPs to all auditory tones except the easy duration target tone, which is 250 ms. This apparent delay may have been caused by a technical problem that delayed the onset of these stimuli. This problem is described in detail in Appendix C. Since the ERP analysis in this thesis was waveform based, all waves were identified based upon this criteria regardless of their latency and the results were therefore internally consistent.

Figure 3.1.2.b   Grand Averaged ERPs for Both Groups in the Active Condition

Continuous line = response to standards, dashed line = response to targets

Easy Pitch   **Hard Pitch**

Frontal

Central

Parietal

Occipital

Easy Duration   **Hard Duration**

Frontal

Controls

Dyslexics

Central

Controls

Dyslexics

Parietal

Controls

Dyslexics

Occipital

Controls

Dyslexics

157
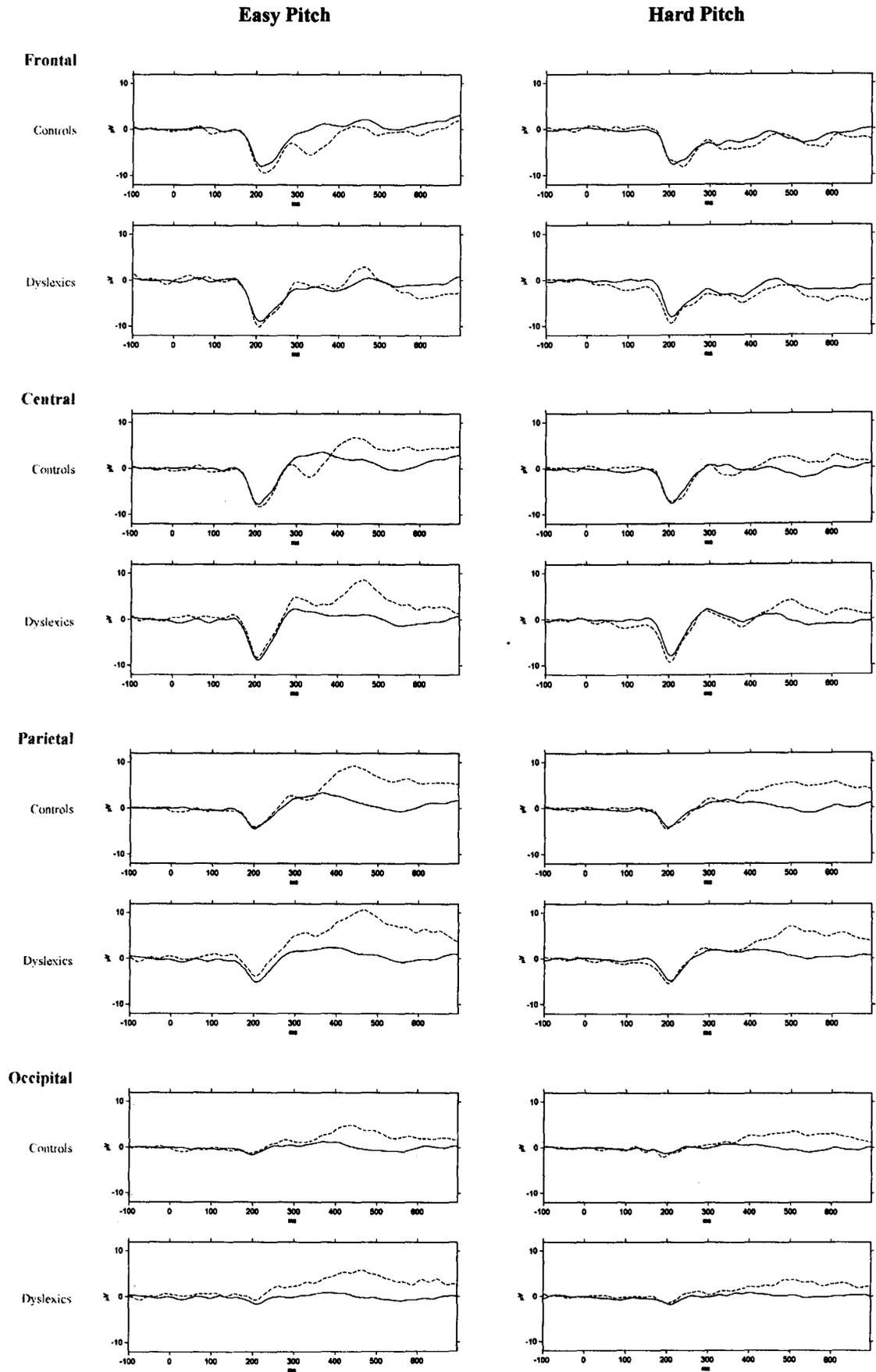
Figure 3.1.2.c   Grand Averaged ERPs for Both Groups in the Familiarized Condition

ERPS for all stimulus conditions are shown in the FM region; Continuous line = response to standards, dashed line = response to hard deviants, and dotted line = response to easy deviants.
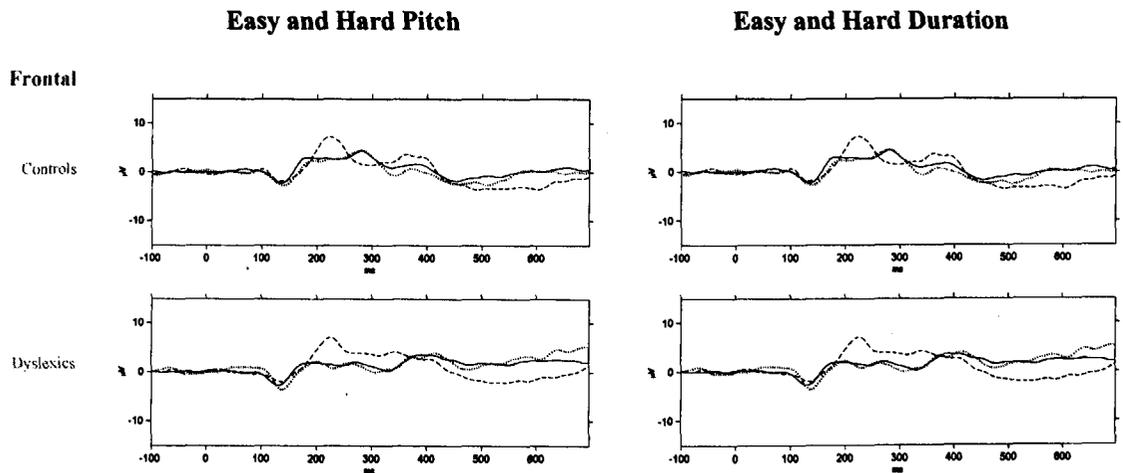
The potentials evoked by standard and target stimuli in controls and dyslexics are shown in Figure 3.1.2 a, b and c. In the passive and familiarized response to all four stimulus conditions, the ERPs to standards and targets in the frontal regions are characterized by small P1 and prominent negative components. The more negative response to deviants has been considered to correspond to mismatch negativity (Näätänen, 1978). After a brief P2 the standards and targets gradually return to baseline. In the active response to all four stimulus conditions, the ERPs to standards and targets in the parietal regions are characterized by small P1 and prominent N1 components. Targets evoke P2, N2 and P3 components, which are attenuated or absent in the response to standards.

Temporal windows around the ERP components of interest were determined by visual inspection of the data from individual subjects, which ensured that the chosen time window captured the component of interest for all subjects. Each wave was defined in terms of being the peak positivity or negativity to standard and target stimuli at selected regions occurring in a selected latency range. These windows are listed in Table 3.1.2.c.

It is important to specify that this nomenclature follows the process based convention for defining ERPs, where MMN is taken as an the additional negativity immediately proceeding N1, as well as the wave form and anatomy based convention adopted in other studies, where MMN is taken as the attention independent equivalent of N2 (Oades and Dittman-Balcar, 1995; Alho, Woods and Algazi, 1992). This is because the deviants evoked negativities in both time windows.

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Table 3.1.2.d Summary of ERP Component Analysis Criteria

S = standard; D = deviant; T = target; F = frontal midline; C = central midline; P = parietal midline; O = occipital midline; Max Amp = amplitude of peak positivity; Max Lat = latency to peak positivity; Min Amp = amplitude of peak negativity; Min Lat = latency to peak negativity; Area = total area of negativity.

Wave	Stimuli	Response	Regions	Time (ms)	Dimensions
Easy Pitch					
N1	S; D	Passive	F	180-240	Min Lat
MMN1	S; D	Passive	F	240-340	Min Amp; Area
MMN2	S; D	Passive	F	340-440	Min Amp; Area
MMN1	S; D	Familiarized	F	240-340	Min Amp; Area
MMN2	S; T	Familiarized	F	340-440	Min Amp; Area
P2	S; T	Active	C; P; O	260-320	Max Amp; Max Lat
N2	S; T	Active	C; P	300-400	Min Amp; Min Lat
P3	S; T	Active	C; P; O	400-520	Max Amp; Max Lat
Hard Pitch					
N1	S; D	Passive	F	180-240	Min Lat
MMN1	S; D	Passive	F	240-340	Min Amp; Area
MMN2	S; D	Passive	F	340-440	Min Amp; Area
MMN1	S; D	Familiarized	F	240-340	Min Amp; Area
MMN2	S; T	Familiarized	F	340-440	Min Amp; Area
P2	S; T	Active	C; P	280-360	Max Amp; Max Lat
N2	S; T	Active	F; C	300-400	Min Amp; Min Lat
P3	S; T	Active	C; P; O	420-540	Max Amp; Max Lat

Table 3.1.2.d (cont)

Waves	Stimuli	Response	ROI	Time	Dimensions
Easy Duration					
N1	S; D	Passive	O	80-140	Min Lat
MMN1	S; D	Passive	O	140-240	Min Amp; Total Area
MMN2	S; D	Passive	O	240-440	Min Amp; Total Area
MMN1	S; D	Familiarized	O	140-240	Min Amp; Total Area
MMN2	S; T	Familiarized	O	240-440	Min Amp; Total Area
P2	S; T	Active	C; P; O	180-240	Max Amp; Max Lat
N2	S; T	Active	C; P	220-340	Min Amp; Min Lat
P3	S; T	Active	C; P; O	300-420	Max Amp; Max Lat
Hard Duration					
N1	S; D	Passive	F	180-240	Min Lat
MMN1	S; D	Passive	F	240-340	Min Amp; Total Area
MMN2	S; D	Passive	F	340-440	Min Amp; Total Area
MMN1	S; D	Familiarized	F	240-340	Min Amp; Total Area
MMN2	S; T	Familiarized	F	340-440	Min Amp; Total Area
P2	S; T	Active	C; P	260-320	Max Amp; Max Lat
N2	S; T	Active	F; C	320-420	Min Amp; Min Lat
P3	S; T	Active	C; P; O	400-540	Max Amp; Max Lat

Data Extraction

For the time window corresponding to the MMN wave, the data for peak negativity and total negative area were extracted, and for the time windows corresponding to the P2 and P3 waves the data for peak positivity and latency to peak were extracted, using MATLAB.

Statistical Analysis

The MMN, P2, N2 and P3 data were analysed using a 2 way repeated measured ANOVA with group (dyslexic versus control) as a between factor, and stimulus type (standard versus target) as a within-subject factor, using Sigma Stat 2.03.

Although the ERP data for all left and right ROIs was also analysed, these results are not the focus of this study and are listed in the appendix.

3.1.3 Results

Behavioural Results

The percentage accuracy as well as the mean reaction times for control and dyslexic groups is shown in Table 2.2.3.a.

Performance:
The overall performance of dyslexic subjects in pitch and duration discrimination, as measured by the percentage correct responses to targets, was significantly worse than that of controls. However, this difference was more significant for the overall (easy and hard) discrimination of pitch deviants [$F(1,29)=4.45$, $p=0.045$] and only approaching significance [$F(1,29)=3.97$, $p=0.57$] for the overall discrimination of duration deviants. As expected, in the within-group comparisons, the percentage of accuracy decreased significantly for the discrimination of harder deviants in both controls and dyslexic groups. However, this difference was highly significant for easy versus hard pitch deviants ($p=0.024$ in controls and $p=0.021$ in dyslexics) and only approaching significance for easy versus hard duration deviants ($p=0.095$ in controls and $p=0.068$ in dyslexics). In the within-stimulus comparisons, the dyslexics' performance was the same as controls in the detection of easy pitch and duration deviants, but their performance was markedly lower than controls in the detection of hard pitch targets (93% in controls versus 76%

in dyslexics) and hard duration targets (92% in controls versus 76% in dyslexics). However these differences did not reach statistical significance. The performance as measured by percentage correct responses to standards was the same for both groups.

Reaction Time:

There was no significant difference in the reaction time of control and dyslexic groups during overall pitch discrimination. However the reaction time of dyslexics was significantly slower during overall duration discrimination compared with controls [$F(1,29)=8.11$, $p=0.008$], with a significant interaction between group and stimulus [$F(1,29)=3.09$, $p=0.09$]. As expected, in the within-group comparisons, the reaction times for the discrimination of harder deviants increased significantly for both controls ($p=0.02$ for pitch and $p=0.001$ for duration) as well as dyslexics ($p=0.05$ for pitch and $p<0.001$ for duration). In the within-stimulus comparison, there was no significant difference between controls and dyslexics in their reaction time during easy pitch ($p=0.26$) or hard pitch ($p=0.40$) discrimination. However, dyslexics were significantly slower than controls during the discrimination of hard duration tones ($p=0.03$) but not easy duration tones ($p=0.44$).

Table 3.1.3.a   Mean Behavioural Measures for Control and Dyslexic Groups

RT to standard stimulus not provided since it required no response.

Condition	% Accuracy				Mean RT (ms)	
	Standards		Targets		Targets	
	Controls	Dyslexics	Controls	Dyslexics	Controls	Dyslexics
Easy Pitch	99.06	98.57	99.06	91.43	443.68	486.99
Hard Pitch	98.36	98.93	92.81	76.43	533.62	566.07
Easy Duration	99.77	99.29	99.69	95.36	345.35	371.90
Hard Duration	99.38	97.77	92.19	75.71	465.57	577.72

Electrophysiological Results

The mean amplitude, area or latency measures of the various ERP waves for the dyslexic and control groups are listed in Table 3.1.3.b. N1 and MMN measures are derived from the passive, while P2, N2, P3 and late P3 measures are derived from the active response condition. The significant differences are described below and summarised in Table 3.1.3.c.

Table 3.1.3.b   Mean ERP Measures for Control and Dyslexic Groups to all Stimuli in the Passive Response Condition

MMN1 and MMN2 show area measures, N1 shows latency measures; Ctrl = controls; Dys = dyslexics.

Wave	Region	Peak Amplitude (μV)				Peak Latency (ms) or Area ((μV^2)			
		Standards		Deviants		Standards		Deviants	
		Ctrl	Dys	Ctrl	Dys	Ctrl	Dys	Ctrl	Dys
Easy Pitch									
N1	FM	-5.54	-5.04	-5.20	-6.40	208.00	209.14	215.50	209.71
MMN1	FM	-3.82	-1.18	-4.80	-4.97	-147.03	122.16	-217.67	-192.94
MMN2	FM	-3.21	-1.85	-3.50	-3.66	-151.53	-63.45	-109.30	-248.15
Hard Pitch									
N1	FM	-4.65	-4.48	-5.54	-3.68	207.50	209.71	208.50	213.71
MMN1	FM	-4.57	-2.69	-5.95	-2.47	-249.28	26.73	-296.18	65.45
	FL	-3.75	-1.98	-4.67	-2.43	-219.87	11.73	-225.96	30.91
	FR	-3.85	-1.46	-5.93	-1.73	-217.98	68.08	-340.12	-43.09
MMN2	FM	-3.97	-2.78	-4.36	-1.92	-238.73	-158.77	-237.94	25.60
Easy Duration									
N1	FM	-0.41	-0.87	-7.73	-4.67	115.00	121.71	127.00	122.40
MMN1	FM	-5.25	-4.96	-9.56	-7.09	-167.64	-174.98	-696.57	-482.90
MMN2	FM	-4.24	-4.93	-5.83	-6.02	-267.28	-256.61	-296.89	-380.75
Hard Duration									
N1	FM	-5.12	-5.17	-6.32	-6.75	206.50	213.71	208.00	220.57
MMN1	FM	-3.47	-3.38	-6.18	-6.25	-157.07	-88.00	-404.63	-450.31
MMN2	FM	-2.92	-2.03	-4.55	-5.11	-76.08	-64.31	-265.17	-319.87

Table 3.1.3.c   Mean ERP Measures for Control and Dyslexic Groups to all Stimuli in the Active Response Condition

Ctrl = controls; Dys = dyslexics; De = easy deviant; Dh = hard deviant.

Wave	Region	Peak Amplitude (µV)				Peak Latency (ms)			
		Standards		Targets		Standards		Targets	
		Ctrl	Dys	Ctrl	Dys	Ctrl	Dys	Ctrl	Dys
Easy Pitch									
P2	FM	0.41	-1.21	-2.01	0.66	300.50	302.29	287.50	301.71
	CM	3.60	3.01	1.85	5.88	301.00	302.29	290.50	302.86
	PM	2.77	2.59	3.23	6.60	303.50	300.00	292.50	304.57
N2	FM	-1.85	-4.33	-6.68	-4.62	328.50	341.71	335.00	346.86
	CM	0.91	-0.86	-3.21	0.30	342.50	343.43	331.50	348.57
P3	CM	3.02	2.15	8.53	9.06	438.50	445.71	442.50	450.86
	PM	2.88	2.56	10.22	11.80	422.50	412.57	448.00	444.00
	OM	1.38	1.13	5.29	7.04	418.50	456.00	435.00	437.71
Hard Pitch									
P2	FM	-0.84	-0.78	-1.18	-1.29	322.00	315.43	308.00	321.14
	CM	2.66	3.45	1.73	3.05	323.50	316.00	301.00	305.71
	PM	3.06	3.09	3.11	3.87	327.50	322.29	318.00	308.57
N2	FM	-4.74	-5.29	-6.32	-6.54	329.50	345.14	348.50	359.43
	CM	-1.62	-1.68	-3.11	-2.74	347.00	348.57	358.50	366.29
P3	CM	0.82	1.81	4.63	4.83	449.50	452.57	474.50	472.00
	PM	1.55	2.56	7.16	7.53	433.50	450.29	483.00	509.14
	OM	1.07	0.96	4.53	4.31	435.00	466.29	488.50	502.86

Table 3.1.3.b (contd)

Wave	Region	Peak Amplitude (μV)				Peak Latency (ms)			
		Standards		Targets		Standards		Targets	
		Ctrl	Dys	Ctrl	Dys	Ctrl	Dys	Ctrl	Dys
Easy Duration									
P2	FM	-2.01	-1.16	-1.53	5.02	180.00	188.00	214.00	218.29
	CM	-2.84	-0.90	**0.86**	**5.44**	180.00	188.00	212.00	210.29
	PM	-1.63	-0.26	3.13	5.05	208.00	196.00	219.00	215.43
N2	FM	-8.20	-7.12	-6.91	-5.48	229.00	226.29	261.50	287.43
	CM	-7.21	-6.17	-3.88	-2.30	223.00	221.14	254.00	254.86
P3	CM	4.08	4.65	9.72	9.81	350.50	338.29	361.00	369.71
	PM	4.09	3.94	11.17	11.92	366.50	365.71	366.50	366.86
	OM	2.17	1.42	**5.42**	**7.53**	371.00	379.43	364.50	370.86
Hard Duration									
P2	FM	-2.30	-1.35	-1.20	-0.80	295.50	293.14	290.50	297.71
	CM	1.35	2.14	**0.01**	**3.56**	298.50	297.71	299.50	298.86
	PM	1.50	1.78	2.38	4.32	295.50	302.29	308.50	302.86
N2	FM	-3.99	-4.72	-7.40	-6.26	359.50	369.71	359.00	364.00
	CM	-1.07	-2.05	-3.18	-1.79	370.00	372.57	349.00	359.43
P3	CM	2.41	1.53	7.85	6.39	455.50	471.43	458.00	453.71
	PM	2.85	2.26	9.19	9.11	**452.50**	**458.86**	**459.50**	**446.86**
	OM	1.13	1.56	4.24	4.95	412.00	442.29	452.00	482.29

Table 3.1.3.d   Mean ERP Measures for Control and Dyslexic Groups to all Stimuli in the Familiarized Response Condition

MMN1 and MMN2 show area measures, N1 shows latency measures; Ctrl = controls; Dys = dyslexics; D easy = easy deviant; D hard = hard deviant.

Wave	Region	Peak Amp						Peak Late					
		S		D easy		D hard		S		D easy		D hard	
		Ctrl	Dys	Ctrl	Dys	Ctrl	Dys	Ctrl	Dys	Ctrl	Dys	Ctrl	Dys
Pitch													
N1	FM	-5.79	-7.38	-5.08	-6.44	-6.41	-6.38						
MMN1	FM	-2.38	-3.85	-3.63	-4.23	-2.52	-4.26	-101.66	-76.12	-96.57	-130.76	1.75	-283.10
	FL	-2.25	-3.49	-2.68	-3.99	-2.34	-3.38	-83.98	-71.06	-53.39	-128.45	-14.31	-172.85
	FR	-2.61	-3.77	-3.47	-4.61	-2.20	-4.17	-89.54	-116.83	-71.22	-183.41	24.81	-262.62
MMN2	FM	-1.48	-1.76	-3.53	-2.58	-1.51	-2.77	-63.94	-24.39	-177.21	-99.36	-67.03	-59.45

Easy Pitch Condition

N1: There were no significant group differences in N1 latency to easy pitch deviants in the passive or familiarized condition.

MMN1: There were no significant group differences in MMN1 amplitude or area to easy pitch deviants in the passive or familiarized response condition. Since the results from the passive condition yielded no difference, no further comparisons between the two conditions were made.

MMN2: There were no significant group differences in MMN2 amplitude or area to easy pitch deviants in the passive or familiarized response condition. Since the groups did not differ in the passive condition, no further comparisons between the two conditions were made.

P2: In dyslexics, the P2 amplitude to targets was significantly greater at CM, PM, and OM in the active response condition.

N2: There were no significant group differences in N2 amplitude or latency to standards or targets in the active response condition.

P3: In dyslexics, the P3 amplitude to targets was significantly greater at OM in the active response condition.

Hard Pitch Condition

N1: There were no significant group differences in N1 latency to hard pitch deviants in the passive or familiarized condition.

MMN1: In dyslexics the MMN1 amplitude to hard pitch deviants was significantly reduced in the passive response condition at FM. The MMN area was also significantly reduced in dyslexics at FM. However, there were no significant group differences in the MMN1 amplitude or area to hard pitch deviants in the familiarized response condition.

Since the results in the passive condition were different from those in the familiarized condition, further analysis of dyslexic and control MMNs in both conditions was conducted. The MMN amplitude and area at the FM as well as FL and FR was analysed, using a 2 way repeated measured ANOVA with group (dyslexic versus control) as a between factor, and condition (passive and familiarized) as a within-subject factor.

MMN1 amplitude: At FM, although there was no significant group difference, the interaction between group and condition was approaching significance [$F(1,29)=3.39$, $p=0.08$]: in the passive condition, the dyslexic MMN amplitude was significantly reduced compared with controls ($p=0.04$). Similarly, at FR, although the group difference was only approaching significance ($p = 0.09$), there was a significant interaction between group and condition [$F(1,29)=5.24$, $p = 0.03$]: in the passive condition the dyslexic MMN amplitude was significantly reduced compared with controls ($p=0.008$). Moreover, in dyslexics, the MMN amplitude was slightly enhanced in the familiarized condition compared with the passive condition ($p=0.07$). No such differences were found in FL.

MMN1 area: At FM, although there was no significant group difference, the interaction between group and condition was approaching significance [$F(3.80)$, $p=0.07$]: in the passive condition, the dyslexic MMN amplitude was significantly reduced compared with controls ($p=0.028$). At FR, there was a significant group difference [$F(1,29)=4.92$, $p = 0.04$] and the interaction between group and condition was approaching significance [$F(1,29)=3.63$, $p=0.07$]: in the passive condition the dyslexic MMN area was very significantly reduced compared with controls ($p=0.008$). Moreover, in dyslexics, the MMN area was slightly enhanced in the familiarized condition compared with the passive condition ($p=0.07$).

MMN2: There were no significant group differences in MMN2 amplitude or area to hard pitch deviants in the passive or familiarized response condition. Since the groups did not differ in the passive condition, no further comparisons between the two conditions were made.

P2: There were no significant group differences in P2 amplitude or latency to standards or targets in the active response condition.

N2: There were no significant group differences in N2 amplitude or latency to standards or targets in the active response condition.

P3: In dyslexics, the group difference in P3 latency to peak in the active condition was approaching significance at PM and OM. Post hoc analysis revealed that at PM the P3 latency to targets was approaching significance and at OM the P3 to standards was significantly delayed.

Easy Duration Condition

N1: There were no significant group differences in N1 latency to easy duration deviants in the passive or familiarized condition.

MMN1: There were no significant group differences in MMN1 amplitude or area to easy duration deviants in the passive or familiarized response condition. Since the results from the passive condition yielded no difference, no further comparisons between the two conditions were made.

MMN2: There were no significant group differences in MMN2 amplitude or area to easy duration deviants in the passive or familiarized response condition. Since the groups did not differ in the passive condition, no further comparisons between the two conditions were made

P2: In dyslexics, the P2 amplitude to targets was significantly greater at CM in the active response condition.

N2: There were no significant group differences in N2 amplitude or latency to standards or targets in the active response condition.

P3: In dyslexics, the P3 amplitude to targets was significantly greater at OM in the active response condition.

Hard Duration Condition

N1: There were no significant group differences in N1 latency to hard duration deviants in the passive or familiarized condition.

MMN1: There were no significant group differences in MMN1 amplitude or area to hard duration deviants in the passive or familiarized response condition Since the results from the passive condition yielded no difference, no further comparisons between the two conditions were made.

MMN2: There were no significant group differences in MMN2 amplitude or area to hard duration deviants in the passive or familiarized response condition. Since the groups did not differ in the passive condition, no further comparisons between the two conditions were made.

P2: In dyslexics, the group difference in P2 amplitude in the active condition was approaching significance at CM and PM. Post hoc analysis revealed that the difference in P2 amplitude to targets was approaching significance.

N2: There were no significant group differences in N2 amplitude or latency to standards or targets in the active response condition.

P3: In dyslexics, the P3 latency to targets as well as standards was significantly delayed at PM in the active condition.

Table 3.1.3.c   Summary of ERP Differences in Dyslexics with Inferential Statistics for Main Effects and Interactions

Diff = direction of ERP wave difference in the dyslexic group; G x S = interaction of group and stimulus; G x s = interaction of standard stimulus within group; G x t = interaction of target stimulus within group; _ = reduced area under response to deviant; ↓ = reduced peak to deviant; ↑ = increased peak to target; ➔ = delayed peak to target; → = delayed peak to standard.

Wave	Region	Diff	Group (1,29) F	p	Stimulus (1,29) F	p	G x S F	p	G x s p	G x t p
Easy Pitch										
P2	CM	↑					11.57	0.005		0.058
	PM				17.60	0.001	11.07	0.005		0.009
P3	OM	↑			163.49	<0.001	6.83	0.021		0.043
Hard Pitch										
MMN	FM	_	5.94	0.03						0.012
P3	PM	➔	3.70.	0.07	35.01	<0.001				0.08
	OM	→	3.56	0.08	19.71	<0.001			0.059	
Easy Duration										
P2	CM	↑	5.44	0.036	15.66	0.002				0.023
P3	OM	↑			78.12	<0.001				0.058
Hard Duration										
P2	CM	↑					3.65	0.07		0.08
P3	PM	➔	6.24	0.027			11.23	0.005		0.08
	PM	→	6.24	0.027			11.23	0.005	0.08	

3.1.4 <u>Discussion</u>

The main findings of interest in the present study can be summarised as follows: the MMN was significantly **smaller** in dyslexics for the hard pitch stimulus condition but not the easy pitch, hard duration or easy duration stimulus conditions. The P2 was significantly **larger** in dyslexics in all stimulus conditions, except hard pitch. The P3 was **larger** in both easy stimulus conditions and **later** in both hard stimulus conditions. There was a significant **improvement** in dyslexic MMN to hard pitch in the familiarised condition compared with their MMN in the passive condition with the same stimulus.

Differences in Exogenous Waves

MMN Differences in the Passive Condition

Abnormal MMN evoked potentials to the discrimination of auditory pitch were recorded in the dyslexics compared with controls, but the MMN to the discrimination of auditory duration were normal, as was the N1 latency to both pitch and duration discrimination. The MMN findings confirm, in an independent set of dyslexics, the theory and previous evidence of a specific impairment in frequency discrimination (Baldeweg, 1999, McAnally and Stein, 1996) that is not related to attention and discriminative cognitive capacity

The functional significance of the N1 and MMN has previously been described. In summary N1 indexes changes in stimulus onset and offset, reflecting the functioning of the transient detector system and MMN indexes the discrimination of sequentially presented sounds, reflecting the functioning of auditory memory (Näätänen, 1992). On the basis of Näätänen's model, the normal N1 latency reflects normal function of the transient detector system, and suggests that the neuronal coding of stimulus onset and offset is unimpaired in dyslexics. However the abnormal MMN amplitude reflects abnormal cortical auditory discrimination accuracy, and suggests that the permanent feature detector system, which decodes and feeds information about the physical stimulus characteristics into sensory memory is selectively impaired for spectral features of the stimulus.

Previous studies with language-impaired children have reported such a selective deficit in frequency discrimination (Baldeweg et. al. 1999; McAnally and Stein, 1996). In a study with dysphasic children, MMN to frequency deviants was more reduced than to duration deviants

(Korpilahti and Lang, 1994). In another comprehensive study in children with language and learning difficulties were more impaired in discriminating consonant-vowel syllables varying in the frequency content of the formant transition (/da/ and /ga/) compared with those varying in the duration of formant transitions (/ba/ and /wa/) and these impairments correlated with reduced MMNs to these phonemes (Kraus et. al., 1996).

Possible Anatomical and Physiological Locus of Auditory Impairment

The findings suggest that dyslexics have no impairments detecting the temporal features of the stimulus, accomplished by neuronal discharges at stimulus onset and offset, but they are selectively impaired in their ability to code or decode the fine spectral features, accomplished by neuronal discharges that are phase locked with the stimulus.

In addition to a possible dysfunction in phase locking mechanisms in the brain stem, these findings may reflect impairments in higher levels of the auditory perceptual system in dyslexia. Brief stimulus characteristics such as binaural phase are encoded in the primary auditory pathway, which includes the ventral division of the medial geniculate body and the primary auditory cortex (Kraus et. al. 1994). However, these structures do not generate MMN potentials, since they do not respond to changes in acoustic sequences (King et. al., 1995). However, MMN potentials have been sourced to non-primary auditory pathways, such as the dorsal division of the medial geniculate body, as well as the secondary auditory cortex (Kraus et. al, 1994).

Moreover, acoustic change detection is thought to have a hierarchical organisation. Discrimination of pure tone and speech contrasts have been shown to evoke MMN at the thalamic level, whereas more complex discriminations such as those required for detecting rapid frequency changes in speech may require contribution from the auditory cortex, particularly the left hemisphere (Baldweg, et. al., 1999).

Links between Frequency Discrimination and Speech Discrimination

Baldeweg and colleagues have proposed that abnormalities in cortical development may render the brain vulnerable to deficits in discrimination of those specific features of speech that require the auditory cortex to process rapid frequency changes (Baldeweg, 1999). Indeed, neuroanatomical and magnetic resonance spectroscopy studies have demonstrated such developmental abnormalities (Baldeweg, 1999). Thus a selective deficit in on line frequency analysis might have similar consequences for the development of phonological skills by leading to noisy or distorted phonological representations. This could provide some explanation for the

delay that dyslexic individuals typically show in acquiring spoken language, that is, the need for greater exposure to new words to enable sufficient and proficient assimilation, and also the subsequent problems of dyslexics in learning grapheme and phoneme associations. Thus, subtle problems in discriminating speech sounds could be a precursor to the marked difficulties experienced by dyslexics in the recognition and manipulation of the sound structure of language (Baldeweg, 1999).

It important to emphasise that this study was not designed to investigate the perceptual difficulties that relate to the ability to process rapidly presented stimuli (Tallal, 1980). The finding of impaired detection of pitch even with relatively long inter stimulus intervals of 1000 ms and 2000 ms indicates that this auditory dysfunction in dyslexics is an even more fundamental problem of auditory perception than one involving the discrimination of rapid acoustic transitions. This is because the present effects (both the perceptual impairments and practice induced perceptual improvements) were obtained with single tone stimuli, which were not rapidly presented and contained no rapid transitions. In fact, the results suggest that certain physical features of the acoustic stimulus may contribute to the temporal processing deficit. Rapid processing is the focus of the next study conducted in this project.

MMN Differences in the Familiarized Condition

In the familiarized passive condition, which followed the attentive condition, the dyslexic MMN to frequency deviants was no longer different from that of controls. Moreover, compared with their pre-practice MMN response, the post-practice MMN amplitude and area in dyslexics was noticeably enhanced in all three frontal regions, and this improvement approached statistical significance in the right frontal region. This finding suggests that the intervening attentive condition resulted in a practice-induced amplification of the dyslexic MMN: the tones differing in only small frequency differences are learned to be discriminated electrophysiologically after relatively short attentive practice. Even small differences are perceived easier and result in a higher activation of the underlying neuronal networks.

To minimise any similarity with the design of the previous active condition, where the subjects were made aware of, and required to respond to, a single deviant type in each block, the design of this condition was changed such that the hard deviants were presented in the same block as the easy deviants. This ensured that, in the event of any attentional effects due to familiarity with the previous design, the hard deviants were still likely to be unexpected and consequently unattended. Therefore, it would be reasonable to assume that the enhanced electrophysiological response to the hard frequency deviants reflected enhanced automatic, non-attentive frequency discrimination, and was not the consequence of any attentional mechanisms. This improvement

in low-level perception following practice might reflect plastic changes in the auditory cortex, resulting in the increased accuracy of cortical frequency representations.

Previous studies have demonstrated changes in the neurophysiological responses of the human central auditory system, particularly at the early automatic neural level of sound discrimination, as reflected in MMN responses in ERP studies (Ahissar *et. al.*, 1992; Näätänen *et. al.*, 1993; Kraus *et. al.*, 1995; Elbert *et. al.*, 1995; Winkler *et. al.*, 1999) as well as MMF (mismatch field) responses in MEG studies (Menning *et. al.*, 2000).

In fact, studies in the visual and auditory modality have revealed that training associated changes in neural activity can actually precede behavioural learning (Karni *et. al.*, 1994; Tremblay *et. al.*, 1998). In one such study auditory evoked potentials were obtained from normal hearing adults in response to two synthetic speech variants of the syllable /ba/ (Tremblay *et. al.*, 1998). Subjects were then trained to distinguish the two variants as being different from each other, and tested both behaviourally and electrophysiologically after each session to determine whether there were any training related changes. It was found that before training the subjects perceived both the variants as identical, but as the subjects learned to identify the 20 ms stimulus as mba and the 10 ms stimulus as /ba/ through training, the duration and area of the their MMN increased as onset latency decreased. A significant and pertinent finding in this study was that whereas individuals showed variable time courses for behavioural learning, all subjects showed significant changes in at least one of the MMN measures by the fourth day, and almost half the subjects showed significant changes in MMN prior to changes in identification ability. The time course of significant behavioural and neurophysiological learning was not the same, and in no case did changes in behaviour precede changes in neurophysiological measurements. In fact, neurophysiological change occurred immediately following the first day of training, well before changes in behavioural learning.

The results of the current study are consistent with these previous reports in normal readers and suggest that training-associated changes in low-level auditory perception in dyslexics can be reliably measured neurophysiologically as early as the first practice or training session in the absence of a behavioural response and before the demonstration of any behavioural learning. The effectiveness of auditory training can be difficult to assess using purely behavioural methods because of compounding attentional or cognitive deficits. However if neurophysiological changes are seen before, and in the absence of, behavioural improvements, this provides an effective means of assessing the efficacy of the training methods at altering the neural representations of the speech/sounds.

Possible Mechanism for the Perceptual Learning during the Active Condition

The very immediate plastic change measured after the active response condition may reflect a fast learning stage, which could have taken place in the auditory system during the attentive session while the brain was selecting optimal sensory units to represent frequency as a unique population of cells firing in synchrony (Tremblay et. al., 1998). In other words, even without conscious awareness, an ensemble of cells in the auditory cortex of the dyslexic's responding in the same manner to both stimuli may have begun to differentiate between the stimuli by establishing distinct synchrony patterns for the 1000 Hz and 1025 Hz tones. Once these codes become efficient, the task became automatic. This process would most likely have been pre-attentive because, judging by their performance in the active task itself, not all dyslexics would have been aware of the salient feature that distinguished the two tones during the initial stages of the discrimination task. Based on the proposed generators of the MMN, this learning probably took place in, but was not limited to, the thalamo-cortical association areas of the auditory cortex (Kraus et. al., 1994).

Subsequent to the fast learning stage, the synchronised events could then consolidate and neural processing could switch from a passive storage mode to an active processing mode. And if the neural information is sufficient to be recognised and integrated cognitively, then the behavioural manifestation of this knowledge can occur. This second stage may be representative of the slow component to learning that occurs offline. Therefore it is possible that the sensory architecture provides the code, but the integration and cognitive retrieval system that recognize this code as being meaningful and sufficient to execute a behavioural perceptual task requires attention and reflects slower learning. Hence the behavioural learning lags behind the automatic, pre-attentive stage, which is why the dyslexics improved in their perceptual abilities in the familiarized condition after the active task, although they were noticeably poorer in that active condition of the task.

Links between Perceptual Training and Reading Improvements

A recent study by Kujala and colleagues with dyslexics measured behavioural and neurophysiological responses before and after training and found that as perception improves, the magnitude of electrophysiological responses increases (Kujala, et. al., 1999). They found that non-linguistic audiovisual training comprising fourteen 10 minute sessions resulted in significant changes in both attentive discrimination, as indexed by reaction time, as well as automatic sound discrimination, as indexed by an enhanced MMN amplitude (Kujala et. al., 2001). Moreover, and more importantly, there was a significant correlation between the change in MMN amplitude and in the reading skills score. The fact that training can alter the early

stage of acoustic processing while also improving reading performance gives support to the view that the reading difficulties in dyslexic individuals, at least in part, stem from bottom-up processing constraints due to an auditory perceptual deficit.

Studies have revealed more significant behavioural and linguistic improvements after more substantive training. Merzenich and colleagues developed adaptive training exercises mounted as computer games, designed to drive improvements in the temporal processing skills of children with language based learning impairments (Merzenich *et. al.*, 1996 Science). With 8 to 16 hours of training during a 20-day period, LLI children improved markedly in their abilities to recognize brief and fast sequences of non-speech and speech stimuli. Tallal and colleagues developed a speech processing algorithm to create more salient versions of the rapidly changing elements in the acoustic waveform of speech that have been shown to be deficiently processed by language-learning impaired children (Tallal *et. al.*, 1996, Science). After extensive daily training, over a 4-week period, with listening exercises in which all speech was translated into this synthetic form LLI children demonstrated significant improvements in speech discrimination and language comprehension abilities.

Differences in Endogenous Waves

P2 Differences

As described previously, amplitude measures provide an index of the allocation of cognitive resources or task difficulty (Khan *et. al.*, 1999). In the present study, an increase in the amplitude of the P2 wave in dyslexics indicates an enhanced allocation of attentional resources for those low-level cognitive functions that are indexed by the P2 wave.

The P2 amplitude is considered to index the early stages of stimulus evaluation and processing (Stelmack and Miles, 1990). Thus in this study, the increase in P2 amplitude in dyslexics during both stimulus discriminations regardless of their difficulty suggests that dyslexics required greater resources for early evaluation of the stimulus, independent of the perceptual parameters.

These findings are consistent with previous findings of abnormal P2 waves in auditory tasks. Holcombe and colleagues reported increased P2 amplitudes in reading disabled children during an oddball task using auditory tones (Holcombe *et. al.*, 1986). More recently, Molfese reported larger P2s in dyslexics using consonant vowel symbols Molfese *et. al.*, 2001). Moreover,

children at risk for reading difficulties showed less asymmetry in P2 component than non-dyslexics during reading tasks, suggesting the use of different cognitive strategies (Khan et. al.).

P3 Differences

The P3 amplitude is held to index a limited central capacity system: it reflects cognitive recourse allocation and task involvement (Kramer, Strayer, & Buckley, 1991). It is related to the top down driven aspects of attention, invested in a particular task (Polich and McIsaac, 1994; Lammers and Badia, 1989), to the updating of working memory (Donchin et. al., 1988) and the evaluation of task relevant stimuli (Donchin and Coles, 1988). Therefore, the increase in P3 amplitude in dyslexics in the easy discrimination conditions of the present study reflects an increased allocation of central attentional resources required for task relevant operations, particularly for the purposes of stimulus evaluation.

Previous studies have reported a lower amplitude P3 wave in developmental dyslexics with visual processing deficits on visual reading related tasks (Taylor and Keenan, 1990) as well as reduced P3 waves in dyslexics on orthographic tasks (McPherson, Ackerman, Holcomb and Dykman, 1998; Taylor and Keenan, 1999), word recognition memory tasks (Stellmack and Miles, 1990) and auditory tasks (Holcomb et. al., 1992; Lovrich and Stamm, 1983, Taylor and Keenan, 1997). The larger amplitude P3 wave in these studies could be due to possible differences in the design and consequently, in the task demands of these experiments.

As described earlier, latency measures of a wave provide an index of cognitive processing time that is independent of response selection, such that shorter latencies are associated with faster processing (Kutas, McArthy and Donchin, 1977; McCarthy and Donchin, 1981). A large body of evidence on the functional significance of the latency of the P3 wave indicates that it is closely related to differences in information processing duration, but unlike reaction time, it is unrelated to any impairment in decision criteria and motor organisation (Kutas, McCarthy and Donchin, 1977; Coles, Gratton, Bashore, Eriksen and Donchin, 1985; Czigler and Balazs, 1998). Polich and his colleagues have proposed that the P3 latency might serve as a temporal measure of the speed of neural activity underlying attention allocation and immediate memory operations (Cohen and Polich, 1997; Polich and Heine, 1996). Also, since P3 occurs after the stimulus has been discriminated and categorized, differences in its latency can be used as a measure of differences in stimulus evaluation time (Kutas et. al., 1977; Polich and Donchin, 1988) independent of response production processes (Duncan Johnson and Kopell, 1981; McCarthy and Donchin, 1981) (Polich, Ladich and Burns, 1990). Therefore, a delay in P3 latency in dyslexics only under the difficult stimulus conditions of the present study indicates that dyslexics were slower to make a conscious discrimination between the stimuli for the

purposes of a response only when the stimuli were less easily distinguishable. This suggests that dyslexics have impairments in the *speed* of stimulus categorisation, the speed being dependent on task difficulty.

Thus, the pattern results for the P3 to targets results suggests that at this stage of stimulus classification, while the easy stimulus conditions require greater attentional resources, the harder stimulus conditions require greater processing time.

It is interesting to note that the group difference in P3 latency to targets is only highly significant in the hard duration condition, and appears to correspond to a highly significant group difference in reaction time to target stimuli. However, the group difference in P3 latency to targets is only approaching significance in the hard pitch condition (although the P3 latency to standards is significantly different), and correspondingly, although there is a marked delay in the reaction time of dyslexics, this does not reach significance.

The delay in the P3 wave to standard stimuli in addition to target stimuli is intriguing. This abnormal response to standards was also observed in both the previous visual experiments (in those cases in the absence of delays in P3 waves to targets) and is therefore clearly multi-modal and quite significant. As suggested in those previous chapters it is quite possible that there are in fact delays in dyslexic responses to both targets and standard stimuli but the magnitude of the effect is smaller with targets because, with only 40 target trials compared with the 160 standard trials, there are not enough of these stimuli to reveal strong group differences. This is supported by the fact that the P3 peaks to targets are noticeably delayed in dyslexics, but simply do not reach statistical significance.

The other possible explanation, which was also suggested previously, is that this deficit is indeed specific to the standard stimulus. It could be that the controls are equally prepared for the presentation of a standard or target stimulus, and simply ignore the standard once it has been classified as the irrelevant stimulus, and respond to the target once it has been classified as the relevant one. However, the dyslexics are in a greater state of readiness to recognise and respond to the relevant target, and therefore whenever the standard stimulus appears, it takes dyslexics a greater time to recognise this irrelevant stimulus and inhibit a response.

The P3 latency differences in dyslexics are consistent with previous reports of abnormal P3 waves in dyslexics in auditory tasks (Holcomb *et. al.*, 1992; Lovrich and Stamm, 1983) and phonological tasks (McPherson, Ackerman, Holcomb and Dykman, 1998). Taylor and Keenan studied dyslexic children with visual processing impairments using three reading related tasks and found delayed N2 and P3 waves in the dyslexics (Taylor and Keenan, 1990). In a later

study, they included a phonological task, with orthographic and semantic tasks, assessing dyslexic children with auditory processing impairments. Latency differences between dyslexics and controls were most marked on the phonological task (Taylor and Keenan, 1999). Both of these studies found the ERP distributions to differ between the dyslexics and controls, consistent with a different cortical utilization in dyslexic children.

Regardless of the precise functional implications of the P2 or P3 waves in this study, two facts are indisputable. There is some low-level cognitive function (indexed by the P2 wave), that is independent of task manipulations, and this function requires a greater allocation of attentional resources. Secondly, there are some high-level cognitive functions in dyslexics (indexed by the P3 and SW waves), that are sensitive to the degree of discriminability of the stimulus, and these functions require a greater amount of time.

In summary, abnormalities in both endogenous components indicate that the dyslexic deficits appear to be linked to more than one stage of stimulus evaluation. Moreover, the deficits are not attributable to knock on, bottom up effects from earlier feature specific sensory deficits since they are observed even in the absence of any abnormalities in exogenous sensory waves. Thus, dyslexics have deficits that are linked to stimulus evaluation and response categorization independent of, and in addition to, any sensory deficits in frequency discrimination.

The results are consistent with previous behavioural findings by Nicolson and Fawcett, that children with dyslexia appear to have a normal speed of processing in a simple reaction task, but are affected when a choice needed to be made, suggesting that the most likely locus of the dyslexics' deficit appears to be the time needed to identify the stimulus (Nicolson and Fawcett, 1994). The findings are also consistent with those from a similar electrophysiological study by Fawcett and Nicolson, in which dyslexic children showed a deficit in the latency of the P3 wave during a selective choice reaction task to auditory tones (Nicolson and Fawcett, 1993). Furthermore, these latencies correlated highly with behavioural selective choice reaction times obtained in their previous study (Nicolson and Fawcett, 1994). Since the latency of the P3 wave is thought to provide an index of stimulus classification speed uncontaminated by response selection factors, these findings taken together provide strong evidence that the deficit in speed of cognitive processing in dyslexic children is not attributable to motor response selection or execution, and appears to be linked to the need to make a discrimination between stimuli.

These findings provide strong support for the automatization theory, which suggests that the dyslexic deficit in speed of processing is caused by bottlenecks, which arise at many stages in central processing as opposed to sensory processing or response preparation. Moreover, the difficulties appear in the absence of any problems with memory load or verbal material. This

theory does not discount possible impairments in perceptual processes, but highlights the existence of independent inefficiencies in the 'central executive' processing system.

3.1.5 <u>Conclusion</u>

1. In accordance with hypothesis 1, this study has identified a difference in the MMN component to subtle changes in tone frequency in the given set of dyslexics, indicating abnormalities in the automatic, pre-attentional discrimination of auditory frequency. This confirms previous behavioural and physiological reports of impaired frequency discrimination in dyslexics using pure tones, the identification of which requires precise temporal coding of frequency (Ahissar *et. al.*, 2000; Baldeweg *et. al.*, 1999; Hari *et. al.*, 1999; McAnally and Stein, 1996), as well as frequency-modulated tones, the identification of which requires sensitivity to temporal cues of frequency (Witton *et. al.*, 1998). No such abnormality was identified in the automatic discrimination of duration, the identification of which requires precise coding of the stimulus envelope.

2. In accordance with hypothesis 2, this study has also revealed, in the given set of dyslexics, differences in the attention-dependent P2, N2 and P3 components, indicating problems with central resource allocation or speed of processing during three different stages of the cognitive sequence. Moreover, some of the differences in these task-related components are sensitive to task difficulty.

3. Finally, in accordance with hypothesis 3, this study has demonstrated an improvement in the MMN responses to frequency discrimination in dyslexics following an attentive practice session.

Thus, these findings have established the co-occurrence of feature-specific perceptual deficits as well as general task-related cognitive deficits in the auditory modality in dyslexia. These results strongly support the view that developmental dyslexia is a multi-level deficit with both low-level and high-level impairments in auditory processing. Moreover, these findings suggest that the improvements in the early, automatic perceptual deficits in dyslexics are possible from a very early stage of practice or training.

3.2 Study 4: Sensory and Cognitive Processing of Rapid Auditory Stimuli

3.2.1 <u>Introduction</u>

The following is the fourth study in this thesis, also called the Auditory Compound (AC) study. In this final study the focus of this research moves to an aspect of processing that is of particular pertinence to this research. The overall objective of these studies was to investigate the co-occurrence of deficits across modalities and across processing stages. By extension, this research sought to investigate the possible co-occurrence of deficits that were implicated in the two neurological theories of dyslexia. A common element of the pan-sensory and cerebellar theories is the suggestion that 'timing' and 'speed' is a fundamental problem area in dyslexia. Temporal processing and speed of processing appears to be impaired at the sensory/ perceptual level, according to the visual and auditory processing theories, and at the cognitive level according to the rapid automatized processing theory, now subsumed by the cerebellar theory. At the sensory level, dyslexics have been shown to have difficulties with both the 'processing of speed', and the 'speed of processing', to use the distinction that has recently been emphasized in the literature (Studdert-Kennedy and Mody 1995, Talcott 1998). At the cognitive level, dyslexics have been shown to have difficulties with their overall speed of processing during cognitive tasks, particularly those where a choice has to be made. Moreover, dyslexics have been found to be impaired in time estimation, which is presumed to be a cerebellar symptom. Thus no research into the processing deficits in dyslexia seems complete without further investigations into these processing deficits.

Rapid Auditory Processing Deficits in Dyslexia

The previous Auditory Simple study investigated timing at the most fundamental sensory level, the actual temporal coding of an auditory stimulus, and found that dyslexics were impaired in the phase locking of auditory frequency. A temporal deficit that has been widely researched and demonstrated in dyslexia at a higher perceptual level is sequential processing or, more specifically, rapid sequential processing.

This temporal auditory deficit has already been described in detail in Section 1.2.5 of Chapter 1. In summary, dyslexics have difficulty in tasks requiring the discrimination between two or more successively presented auditory events. In particular, dyslexics have problems in identifying two tones presented in rapid succession (Reed, 1989) as well as in discriminating the temporal aspects of tonal patterns. This would require the various aspects of sequential processing described in Section A.1.7 of the Appendix, namely stimulus individuation, temporal order sequencing and sequence discrimination (Tallal, 1980).

ERP Indices of Temporal Deficits in Auditory Tasks Dyslexia

Impaired Rapid Sequence Discrimination

A recent study on poor adult readers directly demonstrated differences in evoked responses, specifically magnetoencephalographic responses, recorded from the auditory cortex, and these responses correlated with concurrently measured behavioural deficits in the individuation and discrimination of sequential stimuli (Nagarajan, 1999). The response amplitude evoked by short duration acoustic stimuli was stronger in the post stimulus time range of 150-200 ms and the response amplitude to rapidly successive and brief stimuli that were identical, or that differed significantly in frequency, were substantially weaker for ISIs of 100 or 200 ms but not for 500 ms. Furthermore, these deficits closely paralleled subjects' ability to distinguish between and reconstruct the order of presentation of those stimulus sequences.

A study using functional magnetic resonance imaging (fMRI) study also sought to identify the neurological basis of rapid sequential processing in normal readers and to discover potential differences in that response in dyslexic readers (Temple et. al., 2000). Normal readers showed left prefrontal activity in response to rapidly changing, relative to slowly changing, acoustic stimuli, however dyslexic readers showed no differential left frontal response. Two dyslexic readers who subsequently participated in a remediation program showed increased activity in left prefrontal cortex after training. These fMRI results identify left prefrontal regions as normally being sensitive to rapid relative to slow acoustic stimulation, insensitive to the difference between such stimuli in dyslexic readers, and plastic enough in adulthood to develop such differential sensitivity after intensive training.

Another fMRI study compared brain activities in adult dyslexics and controls during implicit categorical perception of phonemes with both normal and slowed down stimuli (Ruff et. al., 2002). Perception of phonemic contrasts activated a frontal parietal network (Broca's area and the left supramarginal gyrus) in which the frontal component was attenuated by slowed speech

in controls and enhanced in dyslexic subjects, however, no modulation by speech rate was observed in the left supra-marginal gyrus. This enhancement of activity in Broca's area for slowed speech in dyslexic subjects might represent a neural basis of the improvement of performance that has been observed after remediation using this type of stimuli.

MMN as an Index of Temporal Order Discrimination

One study has addressed the pre-attentive processing of sound order as indexed by MMN (Tervaniemi *et. al.*, 1999). ERPs were recorded from reading subjects while they were presented with pairs of two tones differing from each other in frequency (1000 vs. 1500 Hz) such that in the standard pairs the frequencies were in ascending order while in the target pairs their order was reversed. The inter-tone interval was, in separate blocks, varied between 0 and 245 ms to determine the minimum separation in time needed for detecting the reversed order of the two frequencies. Moreover, tone durations of 5 and 20 ms were employed in separate experiments. With the 20-ms stimulus duration, the change-specific MMN component was elicited with all inter-tone intervals employed whereas with the 5-ms stimulus duration MMN was elicited only with the 245 ms ISI but not with 95 ms or shorter ISIs. These findings indicate that the accuracy of the processing of temporal information, specifically tone order reversals, can indeed be probed with MMN and that increasing stimulus duration considerably improves perceiving the order of two tones at the pre-attentive level.

Impaired Discrimination of Temporal Features of Sounds

In addition to differences with rapid sequential stimuli, a few recent studies have also demonstrated significant differences in the ERP components to temporal processing of stimulus patterns (Kujala *et. al.*, 1999; Schulte-Körne *et. al.*, 1999).

In one study Schulte Korne and his colleagues assessed the discrimination of a complex tone pattern in dyslexics and controls. The tone pattern comprised of four short tone segments, of differing pitch, presented without any inter tone interval and the difference between the standard and target patterns was that the second and fourth segments of identical frequency but different duration had been exchanged. Thus the difference between the standard and target stimuli was the temporal rather than the frequency structure, such that the change could not be detected without a representation of the temporal structure of the pattern (Schulte-Körne *et. al.*, 1999). They found that the temporal difference between the patterns triggered an attenuated MMN in dyslexics compared with controls, suggesting that they could not process the temporal information adequately. This finding demonstrated the relevance of temporal pattern processing for dyslexia, as opposed to rapid identification of and discrimination between very brief events

(Schulte-Körne, 1998) and suggested that it may be the temporal information embedded in speed sounds, rather than phonetic information per se that may have resulted in attenuated MMNs found in dyslexics in previous studies.

In a subsequent study, Kujala and her colleagues compared the discrimination of tone pairs and tone patterns in dyslexics (Kujala et. al., 2000). The tone pattern condition comprised of four tones, where the targets differed from the standards in the inter-tone intervals between the two middle tones, and this temporal difference was identical to target and standard in the tone pair condition. Thus the two conditions differed only in terms of overall complexity of stimulus. It was found that, the deviant pattern was discriminated less accurately by the dyslexic subjects, and also elicited a more attenuated MMN in dyslexics, while there was no behavioural or electrophysiological difference in their discrimination of the tone pairs. Since precisely the same stimulus change, which did not elicit an MMN in dyslexics when occurring in the middle of the tone pattern elicited an MMN when it was presented in an acoustically simpler context, this suggested that dyslexics may indeed have difficulty in discriminating temporal sound features surrounded by other sounds.

The work of Tallal, Farmer and Klein and subsequent researchers has proved controversial because there is some disagreement over whether her test really assesses the processing of rapid changes within an acoustic stimulus, or whether it tests the ability to judge the order of rapidly presented acoustic stimuli, since the former might correlate with the rapid temporal processing required for phonological identification of phonemic features but the latter probably would not.

Therefore such research makes it important to appreciate the distinction between 'rate of perception' and 'perception of rate' in order to define a 'temporal processing deficit' (Studdard-Kennedy and Mody). Perception, and by extension, processing, can be said to be temporal only when it depends upon the detection of the temporal properties of a long duration stimulus – i.e. 'perception of rate' - rather than the perception of stimuli with short durations or short inter-stimulus intervals - i.e. 'rate of perception' (Talcott et. al., 1998). Put another way, when the defining features of a long duration stimulus are changing with time (as in dynamic stimuli) this measures the 'processing of rate' and when two or more brief stimuli are rapidly presented (as in sequential stimuli) or have spectral changes over a very short time (that is, tens of milliseconds), this measures 'rate of processing' (Williams and LeCluyse, 1990).

From the mounting evidence it appears that two fundamental aspects of rate of perception are impaired. The 'perception of rate': the perception of the temporal properties of a stimulus pattern. And the 'rate of perception': the perception of stimuli with short durations or short interstimulus intervals.

Aim of Study

The first aim of the study was to determine whether there were any deficits in the given set of dyslexics at the lower levels of auditory perception. The specific mechanism of interest was the automatic, pre-attentive discrimination of rapidly presented tone pairs. This was achieved by taking physiological measurements of the brain's responses to deviant and standard stimuli during a response-free condition, devoid of potentially confounding task-related effects such as attention or cognition. The ERP components of interest were the N1 wave as well as the MMN potential, which indexes the accuracy of pre-attentive discrimination. Based on the findings of Tervaniemi and colleagues in studies with normal readers (Tervaniemi *et. al.*, 1999), the individual tones used in this study were of long and easily detectable durations. This study would reveal whether the deficits in dyslexics extended from impairments in the sensory perception of fine spectral features of acoustic stimuli observed in the previous study, to impairments in the sensory perception of spectral features of brief acoustic stimuli.

This study also sought to examine whether there were any deficits in the given set of dyslexics at higher levels of cognition. The particular task of interest was the conscious, attentive discrimination of the same auditory stimuli used in the previous condition. This was achieved by taking physiological measurements of the brain's responses to the standard and targets stimuli during a selective choice reaction task. The ERP components of interest were the attention-dependent P2, N2 and P3 potentials, which index different stages of task related cognitive processing, such as stimulus evaluation, recognition, categorisation, decision-making and response selection. Both the amplitude and latency of each of these ERP components was measured to enable the assessment of cognitive capacity and resource allocation as well as the speed of processing at each stage of the cognitive sequence. Although previous research into rapid or temporal processing has included a subsequent selective choice reaction task with the same set of stimuli, only the performance data has been recorded in this condition (Nagarajan, 1999, Kujala *et. al.*, 1999; Schulte-Körne *et. al.*, 1999, Kujala *et. al.*, 2003). However the current study hoped to gain further insight into the precise nature and locus of any cognitive impairment by recording ERPs during the response condition.

This study would also enable a comparison of any cognitive deficits in dyslexics with those found in the previous visual and auditory studies using the same dyslexics.

Hypotheses

1. There is a fundamental deficit at the level of perceptual processing in dyslexics, leading to impairments in the automatic, pre-attentive discrimination of rapidly presented stimuli. This

would be reflected in the dyslexics as differences in the amplitude or area of the MMN component to fast but not slow tone order reversals, reflecting impaired rate of processing but intact sequential processing respectively.

2. There is a fundamental deficit at the level of cognitive processing in dyslexia, leading to differences in central resource allocation and/ or speed of processing during one or more stages of the cognitive sequence - stimulus evaluation, recognition, categorisation, decision-making or response selection. This would be reflected in these dyslexics as a difference in the amplitude or latency of one of more of the attention-dependent, task-related P2, N2 and P3 components of their event related potentials.

3.2.2 Methods

Subjects

The subjects were the same as those in the previous experiment (AS). All subject details as well as their recruitment and assessment procedures have been described in the methods section (Section 2.1.2) of Chapter 2.

Experimental Design

Stimulus Conditions

The stimuli were pairs of pure auditory tones, each of 50 ms duration and 75 dB intensity presented binaurally via inner ear headphones. The standard pair consisted of the 1000 Hz tone and 1200 Hz tones used in the simple pitch condition in the previous study. In the deviant pair, the order of these tones was reversed. There were two stimulus conditions in each of which the tone pair presentation was either slow, with an ITI of 250 ms, or fast, with no ITI (Table 2.3.2.a).

The stimulus presentation was based on the oddball paradigm: the infrequent target was pseudo-randomly and occasionally presented amidst the regularly occurring, frequent standard. The standard was presented for 85% trials and the target for 15%.

The experiment comprised two blocks, one for each stimulus condition. Each block consisted of 200 stimuli, comprising 170 standards and 30 targets. Thus, in total the experiment consisted of a total of 400 trials, comprising 340 standards and 60 targets.

In the passive response condition, the stimuli were delivered at a constant inter-stimulus interval of 1200 ms (onset to onset) whereas in the active response conditions the same stimulus sequence was delivered at a constant inter-stimulus interval of 2000 ms (onset to onset) including a 950 ms response wait time.

Table 3.2.2.a   Summary of Stimulus Conditions

ISI = Inter-stimulus interval; Std = standard stimulus; Tar = target stimulus.

Feature	Block	Tone Frequency (Hz)		Tone Duration (ms)		ITI	ISI (ms)	
		Std	Tar	Std	Tar	(ms)	Passive	Active
Speed	Slow	1000-1200	1200-1000	50	50	250	1000	2000
	Fast	1000-1200	1200-1000	50	50	0	1000	2000

Response Conditions

The response condition comprised a passive condition followed by an active condition, both of which were the same as those that were described in the previous auditory experiment. However, in this experiment, no learnt condition was implemented (Table 2.3.2.b).

Table 3.2.2.b   Summary of Response Conditions

Response Condition	Requirements	Mechanisms Involved
Passive	No Attention, No Response	Pre-attentional; Perceptual
Active	Attentive Response	Attentional; Cognitive

Data Acquisition

The behavioural measures were, as in previous experiments, response time and accuracy. The EEG was recorded using the same hardware, software and procedure as has been described in previous experiments.

Data Transformation

Data was transformed using the same procedure and sequence as in previous experiments, and to the same criteria and specifications.

Data Analysis

ERP Wave Analysis

The averaged ERPs for each subject were averaged again to produce grand averaged waveforms for both groups. These grand averaged waveforms are presented below (Figure 3.2.2). Statistical analyses were performed on the averaged ERPs for each subject.

To reduce complexity, 10 regions of interest (ROI) were selected and data from 4-6 electrodes were averaged to produce an ERP for each ROI (see Figure 2.1.2 a). These ROIs were the same as in previous experiments and corresponded to the same GSN electrode positions.

The potentials evoked by standard and target stimuli in controls and dyslexics are shown in Figure 3.2.2. In the passive and familiarized response to both stimulus conditions, the ERPs to standards and targets in the frontal regions are characterized by small P1 and prominent negative components. The more negative response to deviants has been considered to correspond to mismatch negativity (Näätänen, 1978). After a brief P2 the standards and targets gradually return to baseline. In the active response to both stimulus conditions, the ERPs to standards and targets in the parietal regions are characterized by small P1 and prominent N1 components. Targets evoke P2, N2 and P3 components, which are attenuated or absent in the response to standards.

Temporal windows around the ERP components of interest were determined by visual inspection of the data from individual subjects, which ensured that the chosen time window captured the component of interest for all subjects. Each wave was defined in terms of being the peak positivity or negativity to standard and target stimuli at selected regions occurring in a selected latency range. These windows are listed in Table 3.2.2.

It is important to specify that this nomenclature follows the process based convention for defining ERPs, where MMN is taken as an the additional negativity immediately proceeding

N1, as well as the wave form and anatomy based convention adopted in other studies, where MMN is taken as the attention independent equivalent of N2 (Oades and Dittman-Balcar, 1995; Alho, Woods and Algazi, 1992). This is because the deviants evoked negativities in both time windows, as in the previous auditory experiment.

Data Extraction

For the time window corresponding to the MMN wave, the data for peak negativity and total negative area were extracted, and for the time windows corresponding to the P2 and P3 waves the data for peak positivity and latency to peak were extracted, using MATLAB.

Statistical Analysis

The MMN, P2, N2 and P3 data were analysed using a 2 way repeated measured ANOVA with group (dyslexic versus control) as a between factor, and stimulus type (standard versus target) as a within-subject factor, using Sigma Stat 2.03.

[2]**Figure 3.2.2.b   Grand Averaged ERPs for Both Groups in the Passive Condition**

ERPS for all stimulus conditions are shown in the FM region; Continuous line = response to standards, dashed line = response to deviants.

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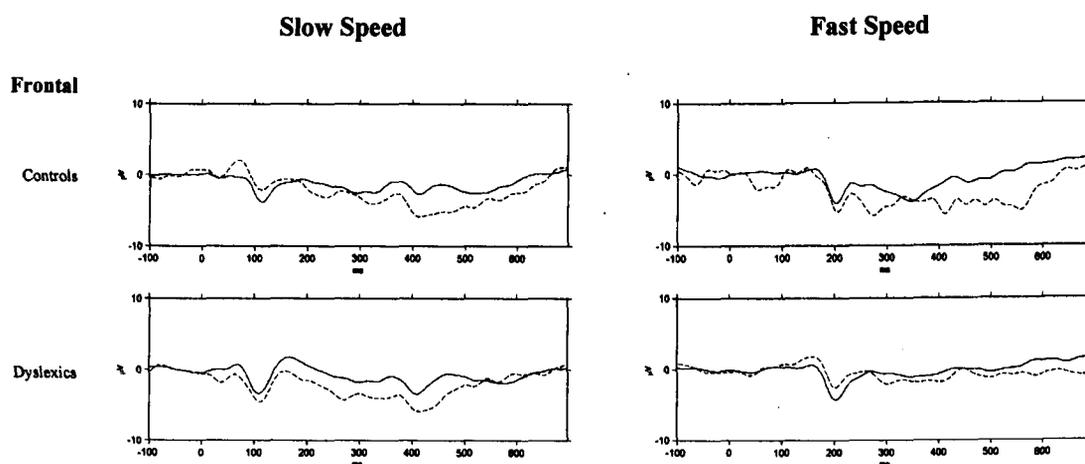
[2] In both of the auditory studies, ERPs to stimuli shorter than ~100 ms duration appear to be delayed by 100 ms. In this study this effect is seen in the passive and active ERPs to the fast speed stimulus pair but not the slow speed pair. This apparent delay may have been caused by a technical problem that delayed the onset of these stimuli. This problem is described in detail in Appendix C. Since the ERP analysis in this thesis was waveform based, all waves were identified based upon this criteria regardless of their latency and the results were therefore internally consistent.

Figure 3.2.2.c   Grand Averaged ERPs for Both Groups in the Active Condition

Continuous line = response to standards, dashed line = response to targets
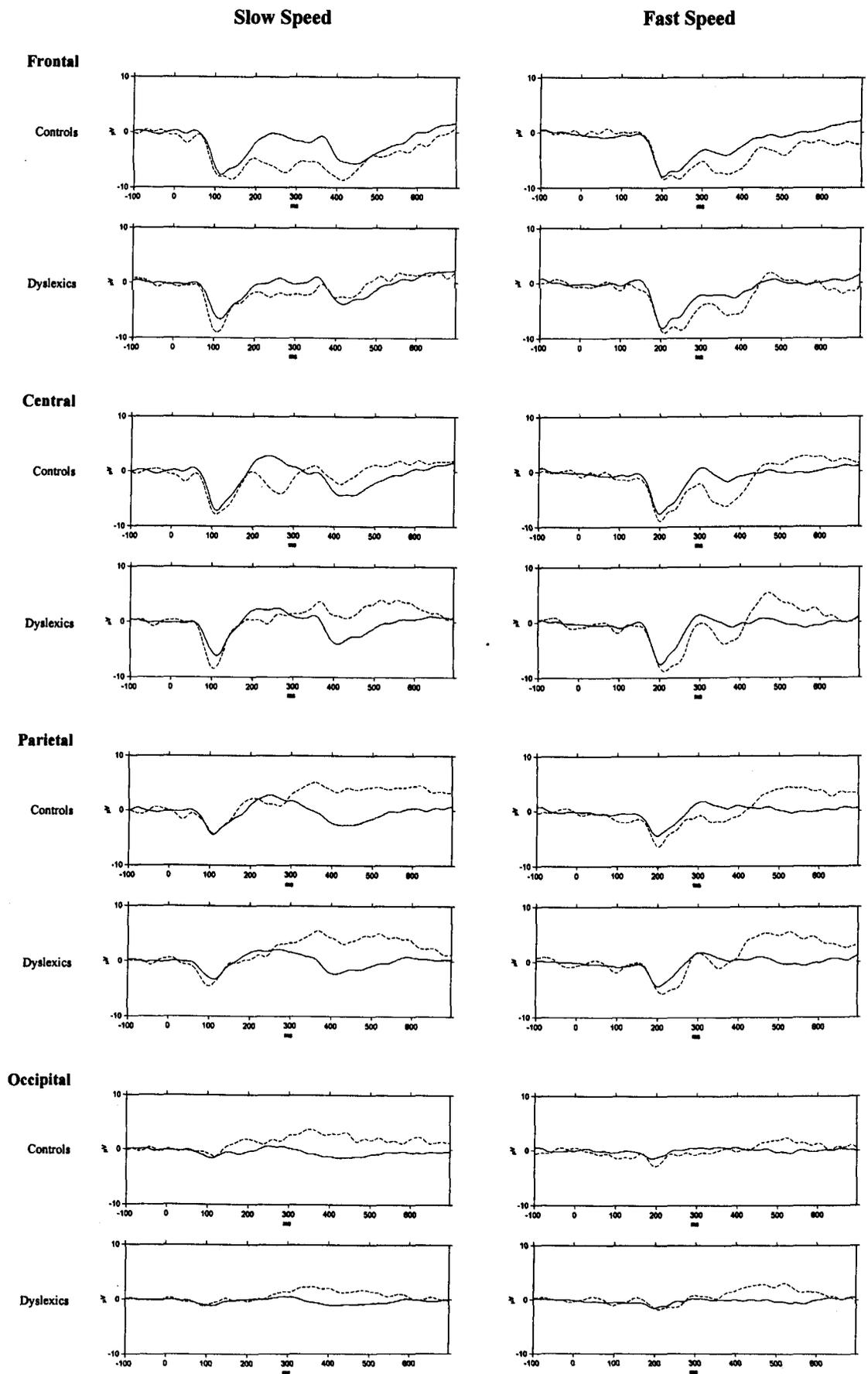
Table 3.2.2.c   Summary of ERP Component Analysis Criteria

S = standard; D = deviant; T = target; F = frontal midline; C = central midline; P = parietal midline; O = occipital midline; Max Amp = amplitude of peak positivity; Max Lat = latency to peak positivity; Min Amp = amplitude of peak negativity; Min Lat = latency to peak negativity; Area = total area of negativity.

Waves	Stimuli	Response	Regions	Time	Dimensions
Slow Speed					
N1	S; D	Passive	F	80-160	Min Lat
MMN1	S; D	Passive	F	160-260	Min Amp; Area
MMN2	S; D	Passive	F	260-460	Min Amp; Area
P2	S; T	Active	C; P; O	170-290	Max Amp; Max Lat
N2	S; T	Active	C; P	220-420	Min Amp; Min Lat
P3	S; T	Active	C; P; O	300-520	Max Amp; Max Lat
Fast Speed					
N1	S; D	Passive	F	180-260	Min Lat
MMN1	S; D	Passive	F	260-360	Min Amp; Area
MMN2	S; D	Passive	F	360-460	Min Amp; Area
P2	S; T	Active	C; P	260-360	Max Amp; Max Lat
N2	S; T	Active	F; C	300-440	Min Amp; Min Lat
P3	S; T	Active	C; P; O	400-640	Max Amp; Max Lat

3.2.3 Results

Behavioural Results

The percentage accuracy as well as the mean reaction times for control and dyslexic groups is shown in Table 2.2.3.a.

Performance:

There was no significant difference in the overall performance of dyslexics and controls as measured by the percentage correct responses to targets or standards [$F(1,29) = 2.14$, p=0.16]. In the within-group comparisons, the percentage of accuracy in dyslexics as measured by correct responses to standards (false positive responses) decreased significantly for the harder discrimination of fast tone-pair reversals (p=0.008). However, this difference was only approaching significance in controls (p=0.062). In the within-stimulus comparisons, there was no difference between dyslexics and controls in the detection of slow speed (p=0.95) and fast speed (p=0.26) tone-pair reversals. The performance as measured by percentage correct responses to targets was the same for both groups.

Reaction Time:

There was no significant difference in the reaction time of control and dyslexic groups during overall (slow and fast) tone pair discrimination. Although, in the within-group comparison, the reaction times for the discrimination of faster deviants increased for both controls as well as dyslexics, these differences did not reach statistical significance. In the within-stimulus comparison, although the dyslexics had markedly slower reaction times to both the slow and fast tone pairs compared with controls, these differences did not statistical significance.

Table 3.2.3.a   Mean Behavioural Measures for Control and Dyslexic Groups

RT to standard stimulus not provided since it required no response.

Condition	% Accuracy				Mean RT (ms)	
	Standard		Target		Target	
	Controls	Dyslexics	Controls	Dyslexics	Controls	Dyslexics
Slow Speed	99.84	99.82	98.13	88.57	430.98	440.65
Fast Speed	99.22	98.84	97.50	87.14	508.04	532.96

Electrophysiological Results

The mean amplitude, area or latency measures of the various ERP waves for the dyslexic and control groups are listed in Table 3.2.3.b. N1 and MMN measures are derived from the passive, while P2, N2, P3 and SW measures are derived from the active response condition. The significant differences are described below and summarised in Table 3.2.3.c.

Table 3.2.3.b   Mean ERP Measures for Control and Dyslexic Groups to all Stimuli in the Passive Response Conditions

MMN1, MMN2 show area measures, N1 waves show latency measures; Ctrl = controls; Dys = dyslexics.

Wave	Region	Peak Amplitude (μV)				Peak Latency (ms) or Area ((μV^2))			
		Standards		Targets		Standards		Targets	
		Ctrl	Dys	Ctrl	Dys	Ctrl	Dys	Ctrl	Dys
Slow Speed									
N1	FM	-4.09	-3.88	-3.19	-5.51				
MMN1	FM	-2.79	-1.57	-4.14	-4.03	-112.12	40.41	-204.58	-180.83
MMN2	FM	-3.07	-2.71	-5.15	-5.85	-216.45	-149.15	-325.21	-390.31
Fast Speed									
N1	FM	-4.44	-4.75	-6.30	-4.02				
MMN1	FM	-4.36	-1.66	**-7.36**	**-3.45**	-162.09	-45.26	**-426.40**	**-118.82**
MMN2	FM	-3.78	-1.60	-7.48	-2.99	-162.09	-45.26	-426.40	-118.82

Table 3.2.3.c   Mean ERP Measures for Control and Dyslexic Groups to all Stimuli in the Active Response Conditions

Ctrl = controls; Dys = dyslexics.

Wave	Region	Peak Amplitude (µV)				Peak Latency (ms)			
		Standards		Targets		Standards		Targets	
		Ctrl	Dys	Ctrl	Dys	Ctrl	Dys	Ctrl	Dys
Slow Speed									
P2	FM	0.40	1.63	-3.64	0.66	248.50	254.29	212.50	236.57
	CM	3.41	3.70	1.18	3.07	233.00	232.00	213.00	242.86
	PM	3.51	2.79	4.45	3.50	238.50	233.14	**225.00**	**274.86**
N2	FM	-5.46	-4.61	-12.01	-7.97	404.00	381.71	322.00	304.00
	CM	-4.53	-4.56	-7.19	-3.95	412.00	393.71	307.00	292.57
P3	CM	1.80	2.68	3.41	6.23	345.50	380.57	403.50	422.29
	PM	1.99	2.06	6.97	8.06	315.50	365.71	415.50	422.86
	OM	0.75	0.70	4.80	4.10 ·	357.00	360.57	375.00	422.29
Fast Speed									
P2	FM	-2.47	-1.30	-3.67	-2.04	312.50	327.43	305.50	306.29
	CM	1.19	2.27	-1.04	0.94	304.50	312.00	**288.50**	**316.00**
	PM	2.27	2.44	0.08	2.59	314.00	322.86	309.50	315.43
N2	FM	-4.67	-3.92	-9.75	-7.78	376.50	362.86	369.50	374.29
	CM	-2.84	-1.96	-8.22	-5.80	379.50	368.57	372.00	365.71
P3	CM	2.08	1.82	5.42	7.58	525.50	571.43	538.00	520.00
	PM	1.85	1.94	6.52	8.19	465.50	545.14	537.00	519.43
	OM	1.07	0.84	3.50	4.30	**443.00**	**569.14**	552.00	520.00

Main Results for Slow Speed Condition

MMN1: There were **no** significant group differences in MMN1 amplitude or area to slow speed deviants in the passive response condition.

MMN2: There were **no** significant group differences in MMN2 amplitude or area to slow speed deviants in the passive response condition.

P2: Although there were no group differences, there was a significant interaction between the dyslexic and control response to target stimuli: in dyslexics, the P2 latency to targets was significantly **delayed** at PL and CL in the active response condition.

N2: There were **no** significant group differences in N2 amplitude or latency to standards or targets in the active response condition.

P3: In dyslexics, the P3 latency to standards was significantly **delayed** at PR in the active response condition.

Main Results for Fast Speed Condition

MMN1: In dyslexics, the MMN1 amplitude to fast speed deviants was significantly **reduced** in the passive response condition at FM, FL and FR (p = 0.04). The MMN area was also significantly reduced in dyslexics at FM.

MMN2: In dyslexics, the MMN2 amplitude to fast speed deviants was noticeably **reduced** at FM in the passive response condition, but this difference did not reach statistical significance.

P2: In dyslexics, the P2 latency to targets was significantly **delayed** at CM in the active condition.

N2: There were **no** significant group differences in N2 amplitude or latency to standards or targets in the active response condition.

P3: In dyslexics, the P3 latency to standards was significantly **delayed** at OM in the active response condition.

Table 3.2.3.c   Summary of ERP Differences in Dyslexics with Inferential Statistics for Main Effects and Interactions

Diff = direction of ERP wave difference in the dyslexic group; G x S = interaction of group and stimulus; G x s = interaction of standard stimulus within group; G x t = interaction of target stimulus within group; _ = reduced area under response to deviant; ↓ = reduced peak to deviant; ↑ = increased peak to target; → = delayed peak to target; → = delayed peak to standard.

Wave	Region	Diff	Group (1,29)		Stimulus		G x S		G x s	G x t
			F	p	F	p	F	p	p	p
P2	PM	→					5.73	0.03		0.013
MMN	FM	↓	4.45	0.055	10.18	0.007				0.037
MMN	FM	_	3.24	0.09						0.08
P2	CM	→	5.28	0.03						0.013
P3	OM	→	5.05	0.043			7.06	0.02	0.002	

3.2.4 Discussion

The main findings of interest in the present study can be summarised as follows: the MMN amplitude was significantly smaller in dyslexics for the fast but not the slow speed condition. The P2 was significantly later in dyslexics for the slow speed and fast speed conditions. The P3 to standards was significantly later for the fast speed condition.

Differences in Exogenous Waves

MMN Differences

Abnormal MMN evoked potentials to the discrimination of the rapid auditory sequences were recorded in the dyslexics compared with controls, but the MMN to the discrimination of slow auditory sequences were normal. The MMN findings confirm, in an independent set of dyslexics, the theory and previous evidence of a specific impairment in frequency discrimination in rapidly presented sequences (Tallal, 1980; Reed, 1989) that is at an automatic preattentive level, independent of any influence from attention and cognitive strategies.

The functional significance of the N1 and MMN has already been discussed. In summary N1 indexes changes in stimulus onset and offset, reflecting the functioning of the transient detector system and MMN indexes the discrimination of sequentially presented sounds, reflecting the functioning of auditory memory (Näätänen, 1992). Moreover, MMN indexes the discrimination accuracy not just of single tones, but also of more complex sound features such as phonemes and the order or pattern of physically different sounds. On the basis of Näätänen's model, the normal N1 latency reflects normal function of the transient detector system, and suggests that the neuronal coding of stimulus onset and offset is unimpaired in dyslexics. However the abnormal MMN amplitude reflects abnormal cortical auditory discrimination accuracy, and suggests that the permanent feature detector system, which decodes and feeds information about the physical stimulus characteristics into sensory memory, is impaired in its function when the auditory tones are presented rapidly.

Based on the findings of Tervaniemi and colleagues in studies with normal readers (Tervaniemi *et. al.*, 1999), which found that rapid order reversals were more easily distinguishable with longer tones, the tones used in this study can be considered to be of long and easily detectable durations. Moreover, the dyslexics did not demonstrate any physiological difficulties in discriminating auditory duration in the previous study. Therefore these MMN differences can be assumed to be related to the rapid rates of presentation rather than the durations of the tones.

Previous studies have indicated that dyslexic children are impaired in identifying brief tones at rapid presentation rates (Tallal, 1980; Reed, 1989) and speech sounds that contain rapid transitions (Reed, 1989). As the performance was impaired in both in the same-different task and in the temporal order judgement task at rapid presentation rates, it was concluded that it is not the perception of temporal order, but rather the sound discrimination underlying successful performance in both tasks that is deficient in dyslexic children (Tallal, 1980). Such impaired discrimination of sounds has also been demonstrated using both pure tones (McAnally and Stein, 1996), the identification of which requires precise temporal coding and frequency-modulated tones, the identification of which requires sensitivity to temporal cues (Witton *et. al.*, 1998).

Taken with the findings of the previous study, these results indicate that the deficits in dyslexics extend from impairments in the *perception of fine spectral features of acoustic stimuli*, to impairments in the *perception of spectral features of brief acoustic stimuli*. Moreover, this is a deficit in the "rate of processing" and is distinct from impairments in perception of the temporal features of acoustic stimuli: they are able to code stimulus onset and offset and discriminate the duration of tones normally. That is, these dyslexics have impairments in rapid processing, as opposed to temporal processing.

It is possible that the permanent feature detector system is unable to decode physical characteristics into sensory memory when the stimuli are presented rapidly due to smaller perceptual windows available for spectral feature discrimination, which is already impaired. Moreover, as a result of this extended time window of perceptual integration in dyslexic individuals, previous sounds could interfere with the identification of later occurring sounds and thereby lead to problems with phonological processing.

What is of particular interest and, indeed, pertinence is that the mild difference in the late MMN response was specific to the left frontal region. This lateralisation of diminished MMN is consistent with a possible left hemisphere dysfunction, particularly for discriminating rapidly changing temporal order changes (Tallal, 1993). This was discussed in some detail in the previous Section 3.2.1.

Differences in Endogenous Waves

P2 Differences

What is particularly interesting in the findings of the present study is that dyslexics show differences in the *latency* of the P2, compared to a difference in *amplitude* in the previous auditory study. Moreover, they show no difference in the latency of the P3 component, in contrast with the previous study.

The functional significance of the P2 component as well as the functional significance of modulations in the amplitudes or latencies of ERP waves has already been addressed during the discussion of the electrophysiological results from the previous experiments. Based on these postulated roles for the P2 wave, the likely explanation for the P2 component latency effect is that greater time was taken in the initial evaluation of the stimulus, since the stimuli in this case comprised tone pairs compared to previous simple, single tone stimuli.

Another explanation for the P2 component latency effect is that the latency is sensitive to differences in "neuro-cognitive strategy" (Kraus *et. al.*,). Thus, it is possible that dyslexics employ a different, longer strategy for performing this task. Temporal order deficits can be distinguished into two types. First, the 'perception of rate', that is, the perception of the temporal properties of a long duration stimulus or the temporal properties of a stimulus pattern. Second, the 'rate of perception': the perception of stimuli with short durations or short interstimulus intervals. This would engage different perceptual and cognitive mechanisms that were not previously required: specifically stimulus individuation, temporal order judgement and

sequence discrimination, and it is likely that the latency of the P2 reflects the difficulty and delay in these mechanisms. In other words, whereas the implementation of the previous strategy engaged more attentional resources in dyslexics, it is possible that the implementation of this strategy took more time.

Regardless of the precise functional implication of the P2 component in this study, one fact is unambiguous. There is some feature-independent, task-related attentional function in dyslexics that requires greater amount of time for completion.

In summary an abnormality in the endogenous P2 component indicates that the dyslexic deficit appears to be linked to stimulus evaluation. Moreover, these deficits are not attributable to bottom up effects from earlier sensory deficits since they are observed even in the absence of any abnormalities in exogenous sensory waves. It is clear that the deficit is also not attributable to motor response selection or execution since it is observed even before the P3 wave, which reflects response categorisation. Dyslexics have deficits that are linked to conscious stimulus evaluation independent of and in addition to any sensory deficits in rapid sequential processing.

P3 Differences

The delay in P3 latency to standard stimuli the hard condition of this experiment, is intriguing. Particularly because this abnormal response to standard stimuli has been observed in all previous experiments: in both the visual experiments as well as both pitch and duration conditions of the previous auditory experiment. A possible reason for this difference has already been discussed in these previous chapters. However, it must be reiterated that there is still very little literature on the functional significance of the P3 response to the frequent and expected standard stimulus, hence it is difficult to speculate too much on the possible implications of these results.

Nonetheless, this finding provides further evidence of abnormalities in the central processes allocated to and associated with the classification and recognition of the standard and target stimuli.

3.2.5 <u>Conclusion</u>

1. In accordance with hypothesis 1, this study has identified a difference in the MMN component to rapid tone order reversals in the given set of dyslexics, indicating abnormalities in

the automatic, pre-attentional discrimination of rapidly presented auditory stimuli. This confirms the previous behavioral reports of impaired rapid sequential discrimination in dyslexics (Tallal and Piercy 1978; Reed 1989; Helenius *et. al.*, 1999; Llinas *et. al.*, 1988).

2. In accordance with hypothesis 2, this study has also revealed, in the given set of dyslexics, differences in the attention-dependent P2, N2 and P3 components, indicating problems with central resource allocation or speed of processing during three different stages of the cognitive sequence.

Thus, these findings have established the co-occurrence of feature-specific perceptual deficits as well as general task-related cognitive deficits in the auditory modality in dyslexia. These results strongly support the view that developmental dyslexia is a multi-level deficit with both low-level and high-level impairments in auditory processing.

Moreover, the findings in this study, taken with those from the previous auditory study and other studies of this nature, suggest that dyslexics have temporal problems at three distinct stages of processing. First, they have difficulties with the *perception of spectral* features of pure and frequency modulated tones, which suggests deficits at the basic descriptive stage of perception, possibly in temporal coding, decoding or tracking of the *frequency* of acoustic stimuli (McAnally and Stein 1996, Baldeweg *et. al.* 1999, Witton *et. al.*, 2002). Second, they have problems with the *perception of temporal features of complex tones*, which suggests possible deficits at the descriptive and integrative stages of perception patterns, possibly in tracking the *timing* patterns of distinct stimuli. Thirdly, they have trouble with the *rate of perception of spectral features* of acoustic stimuli, which suggests deficits at integrative stages of perception (possibly an extended time widow of perceptual integration due to problems in the earlier descriptive stages). Finally, they have difficulties with general *speed of processing* – with the rate of stimulus evaluation or classification – which suggests deficits at higher attentional stages. Apart from the second task, for which they were not tested, the set of dyslexics tested in these studies showed deficits in all the aforementioned tasks, suggesting, what can be termed as 'multi-level temporal deficits'. These findings are a strong indication of the need for further investigations into the full extent and nature of the deficits in timing and speed in dyslexia.

Chapter 4

Concluding Discussion

"The very idea that there is another idea is something gained."

Richard Jefferies, (1848-1887)

4.1 Significance Of Studies

4.1.1 Summary of Issues

The studies in this project sought to determine whether a given set of dyslexics could demonstrate impairments at both levels of processing: sensory/perceptual, as predicted by the pan-sensory theory, and cognitive, as predicted by the automatisation/ cerebellar theory, and in both modalities, visual and auditory.

This was done by testing a group of dyslexic and control adolescents on two visual tasks (VS and VC) and two auditory tasks (AS and AC), which engaged the implicated sensory/ perceptual and attentional processing mechanisms, and then assessing the various putative electrophysiological indexes, exogenous N1 and MMN, mesogenous P2 and N2 and endogenous P3 and SW, of the these various mental processes.

4.1.2 Summary of Results

A summary of all the results in the four studies is presented in Table 4.1.1. In VC, the sensory MMN wave to peripheral stimuli was significantly larger in dyslexics. In both visual studies the cognitive ERP waves were also different: the dyslexic P2 wave was smaller in VS and VC and the dyslexic P3 wave was smaller in VC.

In AS passive, the sensory MMN wave was significantly smaller in dyslexics during subtle pitch discrimination, but was no different during distinct pitch, distinct duration or subtle duration discrimination. In AC passive, the sensory MMN wave was significantly smaller in dyslexics during the discrimination of the temporal order of fast tone pairs, but not of slow tone pairs. In AS and AC active, the cognitive ERPs were significantly different: the dyslexic P2 wave amplitudes were significantly larger to pitch and duration changes and later to temporal order changes. In addition, the dyslexic P3 waves were delayed in the hard pitch and hard duration tasks, while the SW waves were delayed in the easy pitch and duration tasks. Finally, in AS familiarized, the dyslexic MMN wave was no longer attenuated during subtle pitch discrimination as previously observed in the AS familiarized condition.

Table 4.1.1   Summary of Differences in Dyslexic ERPs in all Experiments

MMNp = MMN from passive condition; MMNf = MMN from familiarized condition; _ = reduced area under response to deviant; _ = increased area under response to deviant; ↓ = reduced peak to deviant or target; ↑ = increased peak to target; ➔ = delayed peak to target; → = delayed peak to standard.

Condition	Wave	Difference
I. VS	N1	
Central	MMN	
Field	P2	↓
	N2	
	P3	→

Condition	Wave	Difference
II. VC	N1	
Central	MMN	_
Peripheral	P2	↓
Field	N2	
	P3	→

Condition	Wave	Difference
III. AS	N1	
Easy	MMNp	
Pitch	P2	↑
	N2	↓
	P3	↑
	MMNf	

Condition	Wave	Difference
III. AS	N1	
Hard	MMNp	↓
Pitch	P2	
	N2	➔
	P3	➔ ➔
	MMNf	

Condition	Wave	Difference
III. AS	N1	
Easy	MMNp	
Duration	P2	↑
	N2	
	P3	↑
	MMNf	

Condition	Wave	Difference
III. AS	N1	
Hard	MMNp	
Duration	P2	↑
	N2	
	P3	➔ ➔
	MMNf	

Condition	Wave	Difference
IV. AC	N1	
Slow	MMN	
Speed	P2	➔
	N2	
	P3	→

Condition	Wave	Difference
IV. AC	N1	
Fast	MMN	↓
Speed	P2	➔
	N2	
	P3	→

4.1.3 Overall Conclusions

Inferences from Results

These findings suggest that *the same set of dyslexics* have difficulty in both domains, visual and auditory, and in both aspects of processing, perceptual and attentional. The predictions made at the outset of these studies can now be addressed.

A comparison of the results with the predictions of the main dyslexia theories is presented in Table 4.1.2. In the visual domain, the MMN differences suggest that the dyslexics have perceptual deficits in the processing of stimuli in the peripheral field of vision as predicted by the visual deficit theory. In the auditory domain, the MMN differences suggest that perceptual difficulties are selective and confined to the processing of fine spectral features and rapidly presented spectral features, as predicted by the auditory theory. Therefore the pan-sensory theory correctly predicts the results on all sensory discrimination tasks.

However, in both domains, the conspicuous and consistent P2 or P3 differences suggest that the deficit extends beyond low-level perceptual deficits into more high-level attentional impairments as predicted by the speed of processing and automatization theories. The combined evidence of attenuated or protracted endogenous components in the same set of dyslexics suggests that first, problems with attentional processing among dyslexic readers may be amodal or domain-general, and secondly, these attentional processing deficits occur at both early and later stages of cognitive processing.

Finally, the absence of previous MMN differences after repetitive task performance, suggest the deficit in dyslexics extends to processes involved in automatisation and learning, as predicted by the cerebellar deficit theory. Thus, the cerebellar theory correctly predicts the results on all active and familiarised discrimination tasks. However, the combined pan-sensory–cerebellar deficit theory is an excellent prediction in that it correctly predicts almost all the results, and the only failure is an unfulfilled prediction of deficits in easy cognitive discrimination tasks.

The behavioural results are consistent with the delays in P3 latency to target: differences in both measures are found only in the hard duration discrimination condition.

The present results are encouraging with respect to both understanding and remediating developmental dyslexia.

Table 4.1.2   Comparison of Results with the ERP Predictions for Different Dyslexia Theories on the Range of Tasks Administered

S = name of study; L = level of processing; Phon = Phonological; PSA = combined Pan-Sensory and Automatization; SOP = Speed of Processing; Auto = Automatization; Amp = peak amplitude of wave; Lat = latency to peak of wave; C = cognitive; S = sensory; ⇔ = equivalent; ⇩ = significantly impaired; ⇧ = significantly improved; ✓ = no difference correctly predicted; ✓✓ = difference correctly predicted; ✗ = no difference incorrectly predicted; ✗✗ = difference incorrectly predicted.

S	L	Task	Core Deficit						Results
			Phon	Pan-Sensory		Cerebellar		PSA	
				Visual	Auditory	SOP	Auto		
			Any Amp/Lat	MMN Amp	MMN Amp	P2 N2 P3 Lat	Any Amp/Lat	Any Amp/Lat	Amp/Lat
VS	C	Central	⇔ ✗	⇔ ✗	⇔ ✗	⇩ ✓✓	⇩ ✓✓	⇩ ✓✓	∪ P2A SW
VC	S	Peripheral	⇔ ✗	⇩ ✓✓	⇔ ✗	⇔ ✗	⇔ ✗	⇩ ✓✓	∪ MMN
	C	Central	⇔ ✗	⇔ ✗	⇔ ✗	⇩ ✓✓	⇩ ✓✓	⇩ ✓✓	∪ P2A SW
AS	S	Easy Pitch	⇔ ✓	⇔ ✗	⇔ ✓	⇔ ✓	⇔ ✓	⇔ ✓	⇔
	S	Hard Pitch	⇔ ✗	⇔ ✗	⇩ ✓✓	⇔ ✗	⇔ ✗	⇩ ✓✓	∪ MMN
	S	Easy Durtn	⇔ ✓	⇔ ✓	⇔ ✓	⇔ ✓	⇔ ✓	⇔ ✓✓	⇔
	S	Hard Durtn	⇔ ✓	⇔ ✓	⇔ ✓	⇔ ✓	⇔ ✓	⇔ ✓✓	⇔
	C	Easy Pitch	⇔ ✗	⇔ ✗	⇔ ✗	⇩ ✗✗	⇩ ✓✓	⇩ ✓✓	∪ P2A P3A
	C	Hard Pitch	⇔ ✗	⇔ ✗	⇔ ✗	⇩ ✓✓	⇩ ✓✓	⇩ ✓✓	∪ P2A SW
	C	Easy Durtn	⇔ ✗	⇔ ✗	⇔ ✗	⇩ ✗✗	⇩ ✓✓	⇩ ✓✓	∪ P2A P3A
	C	Hard Durtn	⇔ ✗	⇔ ✗	⇔ ✗	⇩ ✓✓	⇩ ✓✓	⇩ ✓✓	∪ P2A SW
	S	Learned	⇔ ✗	⇔ ✗	⇔ ✗	⇔ ✗	⇧ ✓✓	⇧ ✓✓	∩ MMN
AC	S	Slow Speed	⇔ ✓	⇔ ✓	⇔ ✓	⇔ ✓	⇔ ✓	⇔ ✓✓	⇔
	S	Fast Speed	⇔ ✗	⇔ ✗	⇩ ✓✓	⇔ ✗	⇔ ✗	⇩ ✓✓	∪ MMN
	C	Slow Speed	⇔ ✗	⇔ ✗	⇔ ✗	⇩ ✓✓	⇩ ✓✓	⇩ ✓✓	∪ P2L SW
	C	Fast Speed	⇔ ✗	⇔ ✗	⇔ ✗	⇩ ✓✓	⇩ ✓✓	⇩ ✓✓	∪ P2L SW

Patterns of Results

Some very interesting and consistent patterns in the ERP differences between groups have emerged from the electrophysiological results of all of these studies. In dyslexics:

1. The P2 waves are smaller in the visual, but larger in the auditory tasks.

2. The P2 waves are larger in the single tone, and later in the tone pair auditory tasks.

3. The P3 waves are larger in both easy, and later in both hard auditory tasks.

4. The P3 waves to **targets** are later in the only task that has a difference in **RT**: hard duration.

Ubiquitous P2 Deficits

It is interesting to note that the most robust and reliant marker of dyslexic deficits is the P2 wave. In the visual tasks, this was significantly reduced, in the auditory tasks involving single tone discrimination it was significantly increased, and in the auditory tasks requiring tone pair discrimination, it was significantly delayed. Clearly the perceptual and/or attentional mechanisms indexed by this wave are severely compromised dyslexics, however the nature of this deficit is dependent upon the modality and the task demands. This is consistent with evidence of differences between functional and anatomical generators of endogenous waves in the two modalities (Courchesne *et. al.*).

It is also significant that this wave is considered to have both exogenous and endogenous roles: it is held to index some perceptual mechanisms as well as central functions, including stimulus evaluation and attention allocation. This suggests that dyslexics have difficulties not only in the low-level mechanisms of feature detection and the high-level functions of response categorisation, but possibly at intermediate levels of processing, which might influence and intensify existent sensory or cognitive deficits. There is not much research in which the P2 wave in dyslexics has been closely studied, and these findings suggest the need for further investigations into the functional generators of P2 and the implications of P2 abnormalities in dyslexia.

Selective P3 Deficits

Another point of interest is the selective pattern of deficits in the P3 wave. In the visual tasks it is significantly later, and in the auditory tasks it is significantly larger in the tasks involving

easier discriminations, and significantly later in tasks involving the difficult discriminations. Evidently, the attentional mechanisms reflected by this wave are inefficient or slow only when greater attention or effort is required to meet the task demands. Nonetheless, these changes do not appear to be related to sensory deficits, since they are observed during the discrimination of hard duration deviants, even in the absence of any perceptual deficits. This suggests that dyslexics have modality independent difficulties in the high-level functions of response categorisation.

4.1.4 Limitations of Current Research

The experiments described here leave many possibilities open for further analysis.

Subjects

Since some very mild symptoms of attention deficit are present in one or two dyslexics, it is difficult to determine the respective contribution of the two disorders to ERP abnormalities (Taylor 1995).

Stimuli

Although the present designs largely controlled for stimulus specific effects other than those being tested, counterbalancing the stimuli may serve to reduce the likelihood of any unwanted effects even further.

Electrophysiological Results

Several heterogeneous changes in the group ERPs were noted and have been listed in the results section and briefly discussed in the discussion section. However, these have not been interpreted in much detail for a number of reasons. Firstly, these are not the focus of this project: the stimuli and response conditions were designed specifically to test the MMN to deviants and the P2, N2 and P3 components to targets, and all conclusions are based upon these task based and process based (Muller Gass et. al., 2002) conceptual and analytical frameworks.

There is also potential for some covariance within these waves, and the probable way ahead would be to run further studies to control for such changes or tease out such differences.

Many of the group effects in these studies are not very powerful, possibly due to the small sample size and consequent high variance in the data. Therefore, greater sample sizes would enable more powerful group effects. It should be noted that since the number of participants in each group were fairly small, this experiment may not have had sufficient power to reliably detect all between group effects – null results should therefore be interpreted with some caution.

4.1.5 Directions for Further Research

The present results are encouraging with respect to both understanding and remediating dyslexia.

However, there is much to be gained by extending the research to larger groups to see if any patterns emerge between individual dyslexics. This could then be achieved by across-experiment, within-subject analysis to examine whether the findings are relatively consistent across subjects or whether some dyslexics show consistent deficits in one modality or one information-processing level, in comparison with others. In other words, some dyslexics could be "sensory" and some "cognitive" in their impairments. This would involve taking the mean and SD for the control group and classifying the dyslexics individually as abnormal on a given measure if they were at least 1 SD below the control mean.

Secondly, it would be useful to test a greater number of subjects on a wider variety of tasks tapping into each implicated processing system.

4.2 Implications Of Studies

Despite some disparate results which may be attributed to experimental factors or comorbidity with other disorders such as ADHD, much of the ERP research conducted on dyslexic readers to date suggests differences at the early stages of feature detection, stimulus discrimination and attention, as well as at the later stages of stimulus evaluation and updating in working memory. Moreover, these perceptual and cognitive deficits appear to affect both the visual and auditory domains. The present findings uphold the evidence from recent behavioural, psychophysical and electrophysiological research regarding such deficits among this group of readers. However, they succeed in amassing this evidence in the same set of dyslexics. It is now clear that the same set of dyslexics can be impaired at multiple stages of processing and in at least two modalities. In other words, dyslexics can have concurrent deficits in the visual and auditory systems, and in the systems that process low-level sensory/ perceptual information as well as those that process high-level attentional/ cognitive information.

Galaburda studied various experimental models and suggested that the changes in low-level sensory processors in the brain may be the consequence of earlier developmental changes, taking place in higher-order cortices. Moreover, based on these anatomical discoveries, he suggested the possibility that the sensory/ perceptual deficits could be the consequence, rather than the cause of cognitive deficits, because the latter occur first. Also, he proposed that that primary injury to the cortex may be relatively well tolerated for tasks involving temporal processing, but that it is rather the secondary changes in the thalamus which produce the latter. Instead, the cortical changes may be responsible for other cognitive behaviours that have been described here, and previously in both dyslexics and animal models. Thus "we can be reasonably certain that there are cognitive deficits and perceptual deficits, but we cannot support the idea that the perceptual deficits are causally related to the reading" (**Galaburda, 1999**).

4.2.1 Dyslexia: A Multilevel Syndrome

On the basis of the finding in this thesis, we propose that a single dyslexic brain cannot simply be classed as having "magnocellular", or "cerebellar", or "phonological" impairments, cannot merely be confined to "sensory/ perceptual" or "cognitive/ linguistic" deficits, but needs to be seen as having a functionally and anatomically *global* impairment. The studies in this project revealed multi system impairments in the same dyslexics, supporting the probability that this

could well be a multilevel syndrome caused by selective deficits in a vulnerable network of serial and parallel neurological systems, which can consequently manifest as a visual, auditory, low level and/ or high level processing deficit in the same dyslexic brain.

The Magnocellular and Cerebellar Network

There is no doubt that some dyslexics show magnocellular deficits, and no doubt that others show cerebellar deficits; perhaps these are two sides of the same neuropathological coin. Perhaps it would be useful to see the system implicated in dyslexia as consisting of a susceptible network of both of regions, including their input and output systems. This is not altogether inconsistent with the anatomical map of the implicated regions, the magnocells project to the parietal cortex, which projects to the cerebellum. By this argument, a dyslexic individual could suffer from a particular combination of impairments, rather than magnocellular or cerebellar impairments per se. The impairment might be confined to magnocellular regions or just certain cerebellar regions, or extend throughout this network of nuclei and projections.

The Magnocellular System

Let us start with the magnocellular system. If the deficit is primarily magnocellular, this could cause a cascade of effects, starting with basic sensory and perceptual difficulties in the visual magnocellular pathways and/ or their auditory and vestibular equivalents, to visuo-spatial difficulties in the parietal regions, to difficulties with the acquisition or automatisation of motor and/ or cognitive skill in the cerebellum, all of which have been shown to result in a disruption of the normal development of an efficient phonological system. Moreover, during development, these vulnerable regions could be affected to varying degrees and with varying distributions, thereby explaining the broad spectrum of problems in dyslexics.

The Cerebellum

Alternatively, let us start with the cerebellum. The cerebellum has a prodigious anatomical and functional significance; it contains more than half of all neurons in the brain. Moreover, it has a large number of anatomically and physiologically distinct territories: cerebellar neurons are arranged in a regularly repeating geometrical array of microcircuits, which are mapped in an orderly fashion within the cerebellum (Yeo, 2003). These regions have an appropriate set of sensory inputs from a broad and diffused set of regions, but apply their computational results to very specific output regions. The anatomical and physiological similarity of these microcircuits suggests a consistent type of information processing.

Due to its extensive and organised neuronal circuitry, the cerebellum itself is involved in a wide range of tasks, and therefore within the cerebellum it is possible to have an extensive distribution of deficits. For instance, motor symptoms are most commonly observed in patients who have damage to the superior and medial regions of the cerebellum. By contrast, individuals who have damage to the posterolateral regions of the cerebellum typically have fewer and less severe cerebellar symptoms (Gebhart, Peterson and Thach, 2002). Recent evidence supports a role for the posterolateral cerebellum in higher cognitive function, particularly language. There is evidence that the right posterolateral region of the cerebellum is involved, independently of movement, in helping an individual to generate verbs for given nouns (Peterson, Fox and Posner, 1989) and antonym generation tasks (Gebhart, Peterson and Thach, 2002).

The cerebellar inputs, some of which are magnocellular, are systematically mapped. For instance, the visual magnocellular inputs are to the lateral cerebellum. For most cerebellar regions, there is a strict mapping of outputs upon target motor (or cognitive) structures. For instance, the floculus projects to the vestibular nucleus, which is involved in eye movement control. Dyslexia could be caused by the failure of a vulnerable system that includes various magnocellular inputs (visual, auditory and vestibular) to respective target territories of the cerebellum. Losses or damage could be extremely selective, occurring in some parts of the system and not others. Thus, if the visual magnocellular input pathways favouring lateral cerebellum, or neocerebellum are damaged then testing, for example, vestibular deficits (such as balance), would not test the same territories. Conversely, if the "vestibular magnocellular" inputs innervating the vestibular cerebellum are damaged, then testing for visual deficits would again not test the same regions. Moreover, there is more to go wrong with the system than just its inputs. The pan-sensory magnocellular inputs could be spared and there could be problems with intrinsic cerebellar pathology, such as regional cerebellar losses, in the target areas of these pan-sensory magnocellular inputs.

Phonological processing is one of the cerebellum's defining features. Therefore, one area of consistent damage in dyslexics could be the cerebellar region (including its outputs) critically involved in phonology.

The Pan-Sensory Magnocellular and Cerebellar System

In summary, dyslexics' symptoms could arise because of a selective loss of magnocellular - cerebellar control. This could be mild global loss, including symptoms of dyslexia, or specific loss, which includes or excludes visual, auditory or somatosensory magnocellular inputs. Thus the cerebellar deficits would not be defined by magnocellular deficits, but if the magnocellular

inputs are regional, that is if the visual, auditory and vestibular inputs target different territories of the cerebellum, then dyslexics would show cerebellar symptoms only when the damage occurs in the relevant target areas of the cerebellum, and these would be evidenced only by tasks that test the same relevant territories. The idea of such a pan-sensory magnocellular – cerebellar network, with vulnerable inputs and outputs that are systematically segregated, might provide an adequately "broad yet specific" neuropathology to account for the diversity and disparity in dyslexic symptoms.

4.2.2 Overall Significance of Research

One of the major issues in dyslexia research has been the degree of specificity of the different facets of the deficit. There are those that have argued for a distinction between sensory and phonological subtypes of dyslexia. This distinction has led to enduring controversy in the literature, with a schism between the 'lumpers', who argue that there is a single underlying cause although it may be manifested in different ways, and the 'splitters', who argue that it is better to treat dyslexia as a collection of subtypes (Boder, 1973). This research seems to favour the former argument, or at least support its possibility in a set of dyslexics.

The issue of global or sub-types in dyslexia has both theoretical and applied significance. If, for instance, there is an important distinction to be made between perceptual and cognitive dyslexia, it seems likely that different remediation approaches should be adopted for each subtype. If, on the other hand, there is a single set of causes, it is likely that more generic remediation methods may be developed (Miles, 1994).

On the whole research of this nature is of the utmost importance in both the diagnosis and the treatment of this disorder. Firstly, by understanding the precise biological cause of this disability in the brain it would allow the development of specific non-language based diagnosis methods for dyslexia that can be conducted at an early stage even before the children learn to read and write. This would enable the intervention and support to occur much quicker. Secondly, such research would allow the development of more finely tuned therapies for dyslexia that target just the right areas and functions of the brain. This would enable the remediation and treatment for dyslexia to be even more effective and prevent the long term suffering experienced by so many children with dyslexia.

Appendices

"Results! Why, man, I have gotten a lot of results. I know several thousand things that won't work."

Thomas Edison (1847-1931)

Appendix A   Background

A.1 Information Processing

Background to Information Processing

About thirty years ago, an innovative scientific approach emerged, to help address a question that has been one of the ultimate challenges of both science and philosophy: how the mind works. This revolutionary approach, which has become the most established paradigm for exploring the processes within the brain, is called 'information processing'.

Indeed, the key frontier of neuroscience has always been to understand how the individual nerve cells of the brain can produce all the cognitive functions of the mind. In the 1960s this led to the development of the new integrative discipline of 'cognitive neuroscience', to enable a deeper experimental insight into the workings of the mind. Ten years later, with the advent of computers, the information processing approach in cognitive neuroscience gained momentum to provide a more adequate paradigm for understanding complex mental operations. This approach grew in the 1970s out of an analogy between the operations of the mind and those of a computer. Computers have some of the capabilities of the human mind: they can acquire information, store it in memory, retrieve it, classify it and even modify it. The information processing approach has sought to carve out mental processes into similar components: it is the manner in which the human brain acquires stores, retrieves, interprets and utilizes information.

Thus information processing can be regarded as the transmission and integration of all neural information in the brain, and includes all the lower and higher mental processes that intervene between the input - the stimulus, and the output - the cognitive or motor response. This flow of neural information, from its acquisition in the sensory receptors to its eventual use in cognition and action, is generally thought to involve a series of successive stages in which each stage transforms the outputs of the previous one. The initial sensory components occur in the sense organs and sensory brain regions and include the earlier stages of perception. The subsequent cognitive components occur in higher brain regions and include more complex perceptual stages, as well as attention, learning, memory, thought and language. This paradigm now guides a vast bulk of research in human cognition.

Before describing the various stages and components of information processing that are of particular relevance to this thesis, this caveat by Marvin Minsky, one of the pioneers of cognitive science and artificial intelligence, provides a useful launch pad: "It often does more harm than good to force definitions on things we don't understand. Besides, only in logic and mathematics do definitions ever capture concepts perfectly. The things we deal with in practical life are usually too complicated to be represented by neat, compact expressions. Especially when it comes to understanding minds, we still know so little that we can't be sure our ideas are even aimed in the right directions. In any case, one must not mistake defining things for knowing what they are" (Minsky, 1985).

Perception

Definition of Perception

Early researchers in the study of mental processing found that while the five senses differ in their modes of reception, all the senses share five common steps: First, there is a physical stimulus. Second, a set of events transforms the stimulus into electrical signals in specialized sensory receptors, a process known as transduction. Third, these signals are transmitted as nerve impulses from the sensory receptors to their associated afferent pathways and the corresponding primary sensory areas of the cortex, which results in a 'sensation'. And fourth, the activity of the cells in the afferent pathways and the various sensory regions of the cortex results in the conscious experience of the sensation, or 'perception'. Thus, the sensation is transformed into a percept by such factors as experience and context. Finally, this percept can then be stored in memory, analysed and interpreted further, or used to plan and carry out actions.

Distinctions in Perception

Sensory Physiology and Psychophysics

The findings described above gave rise to the fields of 'sensory physiology' and 'psychophysics'. Sensory physiology focuses on the 'sensation' and examines how the physical energy of the stimulus is transduced by sensory receptors into electrical energy and then coded in the brain. Hence, it examines the basic mechanics of the sensory system: the physics of the medium (light and sound) and the anatomical and physiological properties of the organs (eye and ear).

Psychophysics focuses on 'perception', that is, the relationship between the underlying physical characteristics or properties of the stimulus and the attributes of the conscious experience of these properties. It examines the difference between what there is out there in the world, which is easily defined and measured (physical light intensity, light frequency, sound intensity and sound frequency) and what one experiences as being out there in the world, which is harder to define and measure (brightness, hue, loudness and pitch). The first is physics and the second is psychology – the relation between the two, therefore, is psychophysics.

Top Down and Bottom Up Processing

The stimuli available to our senses are not sources themselves but the effects of certain properties of the sources upon some physical medium such as light or air pressure. Our sense organs can measure these effects and, because the effects depend upon the underlying properties of the object, our perceptual systems can use the measurements of these effects to recover the underlying properties of the sources.

The earliest stage in this process is to reduce the many millions of measurements to more useful 'description' of the informative features of the image. There are two different approaches to how this accounts for what we perceive, both of which are pivotal to all aspects of information processing and, indeed, this project.

Top Down Processing

The top down processing approach maintains that purely descriptive processes are not sufficient to account for perception and the perceiver must actively work out what object could have produced that description. This clearly requires some prior knowledge and this is thought to build a perceptual model of the object that best accounts for the description. According to this approach, the perceiver consciously experiences the perceptual model rather than the image. Because the role of the image is only to provide information or cues that allow the perceiver to choose the appropriate model this approach is commonly termed the indirect approach to perception, emphasizing the tenuous link between the image and the final percept, and viewing the establishment of that link as a form of information processing.

Here the implication is that the chain of events begins at the top. Higher-level systems are first activated and then influence lower level systems. Thus the sensory processing can be influenced by what the subject already knows about the information that is coming into the sensory system, and this information about past experiences are stored in the higher levels of the

system. Evidence for this comes from the fact that the recognition stage of perception is often affected by higher-level knowledge and expectations and shows a 'context effect'.

Bottom Up Processing

The bottom up processing approach maintains that there is no need for perceptual models. Descriptive processes are alone sufficient to account for perception. This view argues that it is misleading to think of the stimulus providing an incomplete representation of the outside world. Rather than considering a single image received by a passive stationary observer, the perceiver can take an active role in controlling the pattern of stimulation. According to this view, perception is concerned with the discovery and description of those aspects of the sensory array or flow that reliably signal relevant properties of objects in the world, known as invariants. The whole process is generally referred to as direct perception. The directness emphasized here is not between the object and the image, but between the image and the percept, because the invariants reliable signal object properties, they can drive perception directly without the need for any perceptual models.

Here implication is that chain of events begins at the bottom: lower level systems describe incoming information with little recourse to higher knowledge and pass this descriptive information onto higher levels for more complex processing.

Most cognitive scientists are content to allow both approaches to coexist. Such compromise involves an initial descriptive stage providing input to a subsequent interpretive stage. According to this invariants provide very powerful cues allowing easy access to the appropriate knowledge. Despite the differences in the two approaches, a compromise seems likely to prove correct because perception is not just a single task but contributes in many ways to many functions. Amongst other things, vision is involved with object recognition and controlling movement and maintaining balance. Some of these tasks are more difficult than others, and it seems likely that some can be accomplished directly whilst others may require more sophisticated internal knowledge and are thus better described by the indirect approach.

Stages of Perception

One computer based framework by David Marr describes visual perception, and by extension perception in general, as a series of stages. The first of these stages is descriptive, and is designed to provide a rich and useful description of the stimulus. The final stage is interpretive, and is concerned with how prior knowledge is matched with the description provided by earlier

stages. Marr's model is thus a combined approach concerned primarily with 'bottom up' processes, but then also including the more 'top down' processing aspects of how knowledge is represented and used in the task of object recognition. It also attempts in the early descriptive stages to provide a neurally realistic account.

Descriptive Processes in Vision

Descriptive processes operating in the first stages of vision break down the stimulus in two ways. First the individual cells operate on small regions of the image and so break it down into tiny fragments. Secondly, each cell is specialized and measures just one aspect of the stimulus so that luminance, colour and motion, for example, are represented in separate neural streams or layers. The end result, according to Marr's notion is a description in which the individual features of the object are represented together with measure of their relevant properties, such as orientation and colour. At this stage, a top down approach can be adopted by using the knowledge of the scene to help find and make sense of the individual fragments, or useful progress can be made with a bottom up approach using the physical properties of the fragments such as their colour to group them together and build larger scale and then much more recognisable features.

In Marr's model the result of the early descriptive processes is the 'Raw Primal Sketch', a list of important image features such as lines and edges, each associated with a description of its relevant properties such as position, orientation, colour and rate of movement. Just as the visual system does, each property shall be dealt with separately here.

The visual cortex is retinotopically mapped: cells in adjacent regions of the retina of the eye project to corresponding cells in adjacent regions of the striate cortex or primary visual cortex (V1) in the brain, so that the retinal map is preserved as a cortical map. These cortical regions, known as hypercolumns, consist of a hierarchy of cells. First the 'simple cells' are thought to receive their input from several adjacent retinal ganglion cells, then outputs of several simple cells might be combined by a 'complex cell', and then outputs of several complex cells are thought to feed into a 'hyper complex cell'.

Feature Detection

In the retina the retinal receptor cells measure the relative amount of light at each point in the image. The cells in the adjacent regions of the retina project to adjacent regions of the striate cortex or primary visual cortex (V1) and these cortical regions, known as hypercolumns, consist of a hierarchy of cells. At the next stage of processing in the cortex, further measurements

begin to refine and add to the description of the important features of the image. All the cells in a hypercolumn have receptive fields with roughly the same orientation and the pattern of response across the hypercolumn cells signals the orientation of the image. The initial cells in the hypercolumn function as feature detectors and signal the presence of a line or edge at that particular orientation and position in the image. The neural hierarchy of each hypercolumn might then build up these features into a more elaborate description for that particular region of the image.

Spatial Frequency

The visual scene can also be analysed in terms of spatial frequency, the rapidity with which the luminance of the visual scene changes in space. The analysis of visual scenes in terms of lines and angles and in terms of spatial frequency is intimately related. Hypercomplex cells responding to particular line lengths and widths can also be characterized as responding to particular spatial frequencies. Hence there are two separate ways of referring to analysis: 'spatial frequencies' for overall global characteristics of pattern analysis and 'features' in terms of specific details of analysis.

Most of psychophysical tests of spatial frequency use a uniform field sinusoidal grating, which is a visual stimulus in which luminance varies over space according to a sine wave function. It is characterised by five parameters: mean intensity or luminance, orientation, phase, contrast and spatial frequency. The gratings can also be modulated with time, to shift from phase to counter-phase at a given frequency.

This is of particular significance in the context of many psychophysics experiments that have been discussed in Section 2 of Chapter 1, which rely on spatial frequency measurements to test early perceptual stages implicated in dyslexia.

Colour Detection

The retinal receptors fall into two general types, rods and cones, and the cones can be further subdivided into three types differing in their sensitivities to wavelength. Hence the first stage of colour vision at the receptor level is trichromatic. The very next stage of the visual pathway, the bipolar cells, then makes comparisons between these wavelength bands.

Motion Detection

The visual system has two separate systems for being able to measure the speed and direction of individual features moving in the image. The first long-range feature tracking system infers motions by tracking changes in position of a fine feature from one instance to the next. The second, short range or motion sensing system appears to measure motion directly by signalling changes in the image continuously over time. These requirements are in place even at the retina. The P type ganglion cells emphasize abrupt spatial changes in the image while the M type ganglion cells function to signal abrupt temporal changes in the image. P cells have small receptive fields and respond only to sharp spatial changes, but give a sustained response throughout the presentation of the stimulus. M cells have larger receptive fields so that they respond to a much broader spatial changes, but typically respond in a transient fashion, only at the onset and offset of the stimulus. Thus P type cells obtain their properties through lateral inhibition, in effect comparing the amount of light at neighbouring positions and respond only when there is a difference across space. M type cells obtain their properties by delayed inhibition, in effect comparing the amount of light at successive times and responding only when there is a difference over time. This segregation beginning at the retina of separate form and motion streams appears to continue throughout the visual pathway up to the middle temporal area of the cortex.

This short-range motion tracking system, of which the M cells are a part, is strongly implicated in dyslexia, and has been discussed in Section 2 of Chapter 1.

Descriptive Processes in Audition

Although such things as edges are obviously important features of an image, it is more difficult to decide what might constitute an important feature of an auditory waveform. However the principles that govern descriptive processes in vision are general enough to apply to all sensory modalities, including hearing. Just as vision starts by measuring such basic properties of the image as luminance, colour and motion, hearing begins by measuring such basic properties of the auditory waveform as frequency and amplitude. And just as visual features are, in effect, changes in these basic properties, so auditory features are changes in the corresponding auditory measures.

Pitch and Timbre Detection

The perceived pitch of a sound is determined largely by rate of repetition of a sound wave, higher frequencies produce higher pitch. The sound quality or timbre of a sound is determined essentially by the shape of the component waveforms. The description of both pitch and timbre begins at the basilar membrane, which forms part of the cochlea.

Periodic sound pressure variations such as pure tones cause the eardrum to vibrate at the same frequency as the stimulus and these vibrations are transmitted by the tiny bones of the middle ear to the oval window of the cochlea. Here each pulse of the vibration causes a pulse to travel along the basilar membrane. Each point of the membrane moves up and down as the pulse travels past and this movement causes mechanical distortion of the hair cells that are arrayed along the membrane e and are auditory receptors.

The distortion causes graded potentials in the receptors, which, in turn, may cause action potentials in the fibres of the auditory nerve that innervates the basilar membrane. The pulse changes in amplitude as it travels along the basilar membrane so that high frequency sounds produce pulses that start large and become smaller, and vice versa. Thus the point on the membrane where the pulse is largest will depend upon the frequency of the stimulus and different sound frequencies will produce action potentials in different fibres of the auditory nerve. For periodic sounds the mechanical distortion of the membrane also occurs periodically. Thus the activity of the auditory nerve fibres is also periodic, with a burst of action potentials for each cycle of the stimulus. This is termed 'phase locking' referring to the fact that action potentials in a given fibre tend to occur at the same position or phase on each cycle of the stimulus.

This aspect of auditory perception is the focus of one of the studies in this project and shall be discussed in more detail in a later section.

When a mixture of two pure tones of reasonably different frequencies is presented simultaneously the membrane breaks it down into its separate components because the resulting wave has peaks at the two positions corresponding to the two frequencies. Moreover at each of these positions the membrane moves up and own at the frequency of the corresponding component, so that the timing of the neural response at each position preserves the frequency of an individual component. More generally, since any waveform can be described as a Fourier series, the membrane will within its mechanical limits break down any waveform into its harmonics with the amplitude of each harmonic being represented by the amount of displacement and its position on the membrane. Thus the resulting pattern of response in the nerve provides a description of the available stimulus that is very like a Fourier series. The identity of each harmonic is driven either by the identity of the responding fibre or the temporal pattern of its response, while the amplitude of each component is given with the total neural activity of the harmonic. This description captures not only the frequency of the stimulus but also the timbre of complex sounds.

Auditory Localisation

Locating the direction of a visual stimulus is fairly straightforward because the image provides a directional map of the external world. In hearing there is no directional map so locating the direction of a sound source is more difficult and measuring its distance is almost impossible.

The two main sources of information about auditory direction rely upon binaural comparisons of the stimulus to the two ears. Sound waves travel relatively slow so that if a sound source is to the left, the waveform will arrive at the left ear before the right. A measurement of this interaural delay provides information about the direction of source because it varies systematically with direction. A second potential measure is provided by binaural comparisons of stimulus intensity. If a sound source is to the left, the stimulus will be more intense in the left ear than the right, and in fact he difference in intensity will vary systematically with the direction of the source. The auditory system makes use of both timing and intensity cues in estimating auditory direction.

In summary, neurophysiology and neuroanatomy have enabled the building of a useful picture of the complex neural machinery that underpins the descriptive stage of perception. The earliest stage comprises the basic neural processes that occur in the sense organs, and involves the measurement of the built in physical features of the stimulus that serve as the elementary units of building blocks of perception. In the case of vision these are brightness and contrast and in audition, loudness and pitch. The neural signals are then conducted further along to the sensory cortex by the afferent sensory nerves. Hence the next stage comprises the more advanced neural processes or cortical processes that occur beyond the retina and inner ear, in the cortex of the brain itself. In this stage the brain starts to put together the sensory information received from these sensory organs.

Integrative Processes in Vision

Descriptive processes operating in the first stages of vision break down the stimulus in two ways. First the individual cells operate on small regions of the image and so break it down into tiny fragments. Secondly, each measures just one aspect of the stimulus so that luminance, colour and motion for example are represented in separate neural streams or layers. The end result, according to Marr's notion is a description in which the individual features of the object are represented together with measure of their relevant properties, such as orientation and colour. At this stage, a top down approach can be adopted by using knowledge of the scene to help find and make sense of the individual fragments. Or useful progress can be made with a bottom up approach using the physical properties of the fragments such as their colour to group

them together and build larger scale and then much more recognisable features. The integrative processes build the initial fragmentary measurements into large clusters, putting back together information about form, colour, motion and depth.

Grouping Processes

The general rules that that the visual system employs to group fragments into larger structures are called the Gestalt rules. The visual system uses these to impose a structure on its fragmentary input and, by doing so, can exploit the fact that the whole is more than the sum of its parts. That is, once the local features have been grouped together, the resulting larger scale structures have new and useful attributes. In Marr's model, the full primal sketch is derived from the raw primal sketch by applying Gestalt grouping rules. It provides a much richer and more useful description than the raw primal sketch capturing much more information about the underlying properties of the external world.

Depth Perception

This image is still flat whereas the real world is solid. The visual system must therefore recover the depth that is lost in producing the image. The fist stage of the visual pathway at which information from the two eyes is combined and consequently where disparity might be measured is cortical area V1. The depth cues add depth to the description of the available stimulus to produce a 2.5D sketch The term 2.5D is intended to emphasise that the resulting description is a depth map of the world seem from one particular view point and not fully 3D because it does not take into account hidden surfaces. While relatively few depth cues are available from the raw primal sketch, the full primal sketch with its explicit representation of such things as texture, provides and ideal basis for depth processing. This 2.5D sketch would be useful in object recognition, where pre stored 3D knowledge about objects could be compared and matched with a description of the current image. In addition, the 2.5D sketch would be useful in a variety of other tasks that can, in principle be accomplished independently of complete recognition, such as helping us to plan and carry out movements about the world.

Integrative Processes in Audition

The waveform produced by even a simple sound source such as a musical instrument is complex and the cochlea produces a description based on harmonic analysis that provides the information needed to ascribe pitch and timbre. In the case of two sources, the auditory system still has the difficult problem of sorting out still more complex waveforms produced by several sound sources: knowing that there are two sources rather than one and deciding which

harmonic belongs to which sound. One solution to this problem is that the auditory system seems to separate out sounds coming from different directions.

Auditory Segmentation

When no directional information is available, we are still able to recognise separate sound sources. This is because different sounds usually have different sound envelopes; the sound produced by one source may rise quickly and decay slowly, whilst another may be more sustained and oscillate gently in both pitch and loudness. Each harmonic will have the same envelope as the overall sound so, in the pattern of activity on the basilar membrane, the set of harmonics associated with one instrument will follow a different time course from those associated with another. Thus two sounds can be segmented by simply grouping together the harmonics that follow similar time courses, and pitch and timbre can then be separately ascribed to each set.

Cognition

"As soon as questions of will or decision or reason or choice of action arise, human science is at a loss."
Noam Chomsky

The next stages of perception mark the transition from the study of relatively 'peripheral' aspects of brain functioning to more 'central' aspects. Finally we arrive at the study of the mental processes that are called 'cognition': finally we begin the study of the mind.

The word cognition comes from the Latin word 'cognoscere', meaning 'to know'; hence cognition refers to the mental process or faculty of 'knowing'. The cognitive processing step is concerned with how the brain further processes sensory information into a conscious perception of the world and enables an interaction within it. It is the ability of the nervous system to recognise, judge and act upon complex stimuli.

Inferential Processes in Vision

Pattern Recognition

The task of pattern or 'object recognition' requires us to match our description of the available stimulus with the appropriate pre-stored knowledge about the objects that originally produced the stimulus. We thus need a way to represent the 3D object structure that is general enough to capture all recognisable objects that can easily be matched with the kind of description provided

by bottom up processes. Rather than trying to represent complete objects, the most obvious approach is to identify a limited set of building blocks from which all objects can be constructed. In Marr's scheme the building blocks are called generalized cones. An important recent extension and alternative theory called 'recognition by components' is based on different kind of building blocks called 'geons'.

This does not require a 2.5D Sketch because the types of decisions required can be made at the level of the full primal sketch. It therefore allows rapid recognition or classification of an object. However it does not provide enough information for a 3D orientation. Thus this scheme should be regarded as a way to bring in knowledge about objects at an earlier stage of visual processing, so that this knowledge can be used in a top down way to guide further descriptive processing. This suggests a much more flexible interaction between bottom up and top down processing than Marr's model. It also highlights the possibility that the visual system uses different descriptions for different purposes. The 2.5D sketch may not be required primarily for visual object recognition because this can be achieved more directly from the 2D information provided by the full primal sketch. Instead the 2.5 D sketch may be needed in different tasks like manipulation and locomotion.

Inferential Processes in Audition

Speech Recognition

Speech recognition is a rather specialized and refined form of auditory recognition although reassuringly it seems to follow the same general principles as visual recognition. Like vision, the first step is to define a set of building blocks from which all speech sounds can be constructed. Neither words nor syllables are suitable for this because there are just too many of them. Instead, the most obvious candidate is the basic speech sound called a phoneme. Only about 50 phonemes are needed to describe all human languages and most languages make use of far fewer than this.

Phonemes are, of course, only useful if they can easily be recovered from the descriptions by bottom up processes. At fist this appears a formidable task because many phonemes don't have an obvious measurable physical basis. Vowel sounds have a clearly perceivable pitch because they are periodic and so have a clear harmonic structure consisting of discrete bands of frequencies called formants. Another type of speech sound called voiced stops seems to involve changes in the frequencies of these formants, called formant transitions. Unfortunately these transitions depend crucially upon their context, so that, the same phoneme can be signalled by very different transitions depending on what immediately precedes it.

These speech sounds are indeed, more easily understood in a meaningful rather than a meaningless context which does indicate the importance of high-level knowledge in speech recognition. None the less, contemporary theories propose a more even balance between bottom-up and top-down processing, akin to that proposed for visual object recognition. The key to this emphasis is the realization that physical cues to phonemes are in fact present in the speech waveform, if only one knows what to look for. Each phoneme produces a unique pattern of results in terms of rate of change of amplitude and frequency. This emphasis on patterns of descriptions is reminiscent of what is thought to happen in vision. Moreover the emphasis on changes rather than fixed values fits well with the general definition of features and with the types of measure that the cells in the auditory cortex seem to make.

Parallel and Serial Processing

Hence perception involves two kinds of processing. Simultaneous or 'parallel processing' is the processing of the segregated primitive features by different feature detectors at the same time. Consecutive or 'serial processing' is the processing of the perceived segregated features of the stimulus, where each step occurs one after the other, with the completion of the previous step necessary for or enabling the next one.

It seems therefore that the first cortical processes occur simultaneously or in parallel. Parallel processing is the processing of the segregated, primitive features of the stimulus by different feature detectors at the same time. And consecutive or 'serial processing' of the perceived segregated features of the stimulus, where each step occurs one after the other, with the completion of the previous step necessary for or enabling the next one.

Attention

Definition of Attention

Our perceptual system organises the patchwork of different sensations into a coherent whole that has meaning, and this results from bottom up and top down processing. But perception must be, and indeed is, selective. Our ability to take in and interpret the myriad sensations is finite, so our perceptual system is forced to choose among them. The various ways in which we exercise such choices and perceive selectively, are grouped together under the general label of selective perception or 'attention'. Thus the role of attention is to regulate perceptions.

The most direct way of selecting the input is to orientate the sensory systems physically towards one set of stimuli and away from the other, known as 'physical orientation'. These orienting adjustments of the sensory machinery are the external manifestations of attention and these determine the sensory input that the perceptual system receives.

But selective control of perception may also apply central selective processes, in the higher cortical areas or association areas, known as 'central selection', which determine whether a particular portion of the sensory input will be dealt with further and if so how it will be interpreted. This central selection is another form of 'top down' processing, since what is selected for further perception is guided by prior knowledge and expectations, independent of the primitive stimulus features. In vision for example the most widely used method for studying visual attention is the visual search procedure, and in audition, it is dichotic presentation.

Thus the attentive process can be thought of as a 'flashlight' that selects and highlights the still segregated features of the stimulus that will be further processed, and performs three basic functions. Selective attention chooses what is to be processed from the environment, that is, where the flashlight is to be pointed. Focused attention involves the efforts necessary to sustain processing of the chosen stimuli while avoiding other stimuli that are distracting, that is, keeping the flashlight beam pointed on the chosen object. Divided attention is the ability to process several stimuli from the environment at the same time and this usually only can be performed successfully when different cognitive resources are required for each stimulus.

Central attention therefore acts as a kind of filter, interposed between the initial stages of sensory registration and later stages of perceptual analysis. If the information is allowed through, it can then be further analysed, specifically, it can be recognised, interpreted and stored in memory. But if it does not pass through, then much of it is lost. However, it is important for the purposes of this thesis to point out that this filtering effect is not all or none, and the information is still detected and initially discriminated, even if not interpreted or remembered.

One of the difficulties of studying attention is that it is a concept that is easy to grasp intuitively but difficult to define or test objectively. Thought attention is a central and seminal concept in cognition, there is no completely accepted model of its components or processes and little consensus as to how they should be identified (Moores. Nicolson and Fawcett, 2003).

Models of Attention

An early concept of attention considered it a method of coping with the limited capacity of the human information processing system. Since the processing capacity is limited, attention is a means of directing the processing resources to key information.

Filter Models of Selective Attention

Early Selection Filter Models

These models assume that the selection of information occurs at an early stage of information processing due to the limited capacity of the processing system. It proposes that only one stream of information is attended to and makes it past the attentional filter to be processes further, while other information is left unattended and unprocessed. The filter model by Broadbent proposes that this early selection is based on conscious choice, specifically, on the physical characteristics of the stimuli. Attention is then switched to the chosen channel and the only the selected stimulus receives deeper perceptual processing, while everything else is completely blocked out and receives no further processing. However, evidence against this model is that a persons name draws attention even when unattended. The attenuation model by Tresiman (1960) is similar to Broadbent's model in that it proposes that selection occurs early due to the limited capacity of the system. However it differs from Broadbent's model in that is suggests that the filter is not 'all or none', but simply attenuates or turns down the volume of other stimuli.

Late Selection Filter Models

These models are based on Deutsch and Deutsch (1963) and Norman (1968) and assume that all information is makes it passed the filter and is fully processed. Selective attention acts at the level of response, so that response is only made to the attended stimuli. Evidence for these models comes from the semantic priming effects demonstrated in lexical tasks by Marcel (1983).

Preattentive and Attentive Processing

Perceptual processing can be seen to involve two distinct sequential processes: preattentive and attentive (Treisman, 1960). Preattentive processing does not involve central attention and is used with simpler stimuli. Also, it involves simultaneous or 'parallel processing', that is, it involves the perception of segregated primitive features by different feature detectors at the same time. In vision, for instance, it includes the perception of depth, motion and form. Attentive processing involves central attention and is used with more complex stimuli. Also, it

involves consecutive or 'serial processing' of the still segregated features of the stimulus, that is, each step occurs one after the other, with the completion of the previous step necessary for or enabling the next one.

Componential Models of Selective Attention

Following a series of critiques this unitary 'resources' framework was largely replaced by a newer one, attempting to distinguish between different components of attention. According to the 'componential' framework, there are three key aspects or components of attention: 'selective attention', which involves narrowing focus on selected information, 'switching attention', which involves moving focus from one stimulus to another, and 'sustained attention', which involves maintaining focus over extended periods of time (**Moores et. al., 2003**).

Visual Spatial Models of Attention

When all stimuli are presented sequentially and in the same position, attention is non-spatial and thus selective, shifting and sustained attention occurs in time, rather than in space. However, when stimuli are presented in different positions in the visual field, this introduces a spatial component to visual attention. The cognitive operations that allow the selection of a particular area of the visual field where the processing of relevant information is facilitated comprise 'spatial visual attention'. It involves two essential components, attention focusing and attention orienting. Attention focusing consists in adjusting the attentional width to the size of the observed object, and consists of two elementary mental operations: one that enables the shifting of attention from a distributed or diffused modality to a more focused modality (attention shifting and attention selection) and the other that inhibits lateral distraction (**Facoetti et. al., 1999**). Attention orienting consists in moving the focus across the visual field toward a target, and may be considered in terms of three elementary mental operations (Posner, 1980): disengaging the focus of attention from the current position, moving of attention to the target location, and engaging the focus of attention to the new target position.

Higher Cognitive Systems

The percepts that are selected and attended to are passed along the information-processing pathway to the higher cognitive system. While the lower cognitive functions include perception, the higher cognitive functions are those that require more complex cognitive processing, and include thinking, memory, and language.

Thinking

Thinking may be defined as any mental operation that relates two or more bits of information explicitly or implicitly. A host of complex cognitive functions is subsumed under the rubric of thinking: computation functions (reasoning and judgment), conceptual functions (abstracting, generalizing, and categorizing), problem solving and decision-making functions, executive functions (preparing, planning and selecting a response) and expressive functions (observable responses, actions and behaviours).

Decision Making Functions

In the higher cognitive system the stream of percepts provided by the perceptual system is analysed, and judgements made as to what is going on in the outside world. This enables an awareness of that outside world. However, awareness per se adds little value to an organism, and for an experience to be worth having, it needs to be remembered, which requires short-term memory. Decision-making is the process followed when choosing what response to make based on a perceived stimulus. The process followed can vary greatly depending upon the decision context and the type of decision strategy applied. When making decisions, long-term memory can be referred to, if needed. Furthermore, if additional resources are required, that is to say, if problem solving is required before a decision can be made, then a temporary "problem space" is set up in a two way 'working memory', and accessed as needed. The end result is that some sort of willed behaviour is decided upon, and the necessary instructions are passed down the information-processing pathway to initiate it. Consciously initiated behaviour can often conflict with behaviour initiated via the subconscious routes, so somehow the best balance of willed and unwilled behaviours needs to be selected. This final 'response selection' is passed down pathway to the motor system to execute an action or give a response.

Executive Functions

Executive Functions include operations that involve preparation, planning, choosing, coordinating and alternating an action. Decision-making may be considered a stage of information processing which falls between perception and an executive function.

Memory and Learning

Definitions of Memory and Learning

Where perception concerns the organization of space, memory concerns the organization of time. It is the way in which we record information for later use.

There are three stages of memory: encoding, storage and retrieval. Encoding refers to the transformation of information that has been acquired or learned into a kind of code or representation that can be placed in the memory. It includes consolidation, the process that alters the newly encoded and still labile information so as to make it more stable for long-term storage. Storage refers to the retention of the encoded information in the memory. Finally retrieval refers to the recovery of the stored information from memory.

Distinctions in Memory and Learning

There are a number of fundamental distinctions in memory. Based upon the kind of situation, memories can be short term or long term and based upon the kind of information, memories can be explicit or implicit.

Short Term Memory

Short-term memory is the short-term storage system that falls between the sensation/perception stages and long-term memory storage stages of information processing.

Encoding of information into the short-term memory requires that we attend to it; hence it depends upon what is selected and attended to. Storage of information in short-term memory is very limited, since it has a very limited capacity. As a result, many items are forgotten due to decay with time or displacement by newer items. Retrieval from short-term memory slows down as the number of items in short-term memory increase, suggesting that retrieval may involve a search in which the items are examined one at a time. If information in short tem memory is to persist, it must be transferred to long-term memory. One theory about this transfer suggests that information we have attended to enters short-term memory wherein it can be either maintained by rehearsal or lost by displacement or decay. In addition information can be transferred to long-term memory, most commonly by rehearsal.

Hence, short-term memory can be considered to be the loading platform into the huge long-term warehouse, where materials are allowed to remain for a very short time, and from where they are either picked up and placed in the warehouse, or removed. Hence information in short term

memory is very short lived, and is either rapidly forgotten due to decay or displacement, or transferred into long-term memory by an essentially mechanical process, such as rehearsal.

Working Memory

However, more recently theorists believe that short-term memory is not so much a short term loading platform, but a mental workbench where various items are encoded. This gave rise to the term 'working memory', to focus on the way in which memories are processed rather than held. Hence what is limited in this memory is not the storage area but the amount of processing that can be accomplished and what determines whether the memories will be retrievable depends on how it is processed, that is, encoded and recoded. Such working memories do not get transferred into long-term memory, rather they are held temporarily and then forgotten.

Short-term memory has three component systems. An attentional control or central executive system actively focuses perception on specific events in the environment. This system then regulates the flow of information to two complimentary 'rehearsal' systems that are thought to store information for temporary use and are controlled by the central executive. The articulatory loop comprises the 'inner voice' that stores spoken words and the 'inner ear' that stores sounds to be remembered or recalled. The visuospatial sketchpad is the 'inner eye' that stores the visual properties and the spatial location of objects to be remembered or recalled. The information processed in either one of these systems has the possibility of entering long-term memory.

Long Term Memory

Long-term memory is the "final" storage area of the human memory model. This is the destination store where both explicit and implicit information is retained. It is different from short term in that there are interactions between encoding and retrieval. Operations carried out during encoding, such as elaboration, organising and context make retrieval easier. Storage is strengthened by associating information with other memories and information structures.

Explicit Memory

Explicit memory is the information about 'what', i.e., it is the 'knowledge' of facts and events and what they mean. This memory involves learning that is reflective rather than reflexive in nature, and requires deliberate and conscious effort. Explicit memory can be further classified as episodic, a memory for events of past personal life, or semantic, a memory for facts of

general knowledge. Both are the result of at least four distinct processes of encoding, consolidation, storage and retrieval.

Implicit Memory

Implicit memory is the information about 'how', i.e., it is the 'skills' to perform a task. This memory involves learning that, firstly, tends to be reflexive in nature, so that it is involved with training perceptual, cognitive or motor 'skills' and, secondly, does not require conscious awareness. Unlike explicit memory, implicit memory storage does not depend upon conscious learning processes nor does its retrieval require a deliberate search of memory. This type of memory builds up slowly, through repetition over many trials, and is expressed primarily in performance, not in words. These include perceptual and motor skills and the learning of certain types of procedures; hence it is also referred to as procedural memory.

On the basis of learning, implicit memory can be further classified as non-associative, where the subject learns about the properties of a single stimulus, by being exposed once or repeatedly to a single type of stimulus, and associative, where the subject learns about the relationship between two stimuli, or between a stimulus and behaviour.

Two forms of non associative learning are common: habituation, which is a decrease in response to a benign stimulus when that stimulus is presented repeatedly, and sensitisation, which is an enhanced response to a wide variety of stimuli after the presentation of an intense or noxious stimulus. Both these forms of learning are not dependent upon the relative timing of the intense or weak stimulus and no association between two stimuli is needed.

Two forms of associative learning have been distinguished: classical conditioning, which involves learning a relationship between two stimuli, and operant conditioning, which involves learning a relationship between the subject's behaviour and the consequences of that behaviour, that is, associating a specific behaviour with a reinforcing event. In both forms of learning, the timing is crucial and the predictive relationships between the two stimuli or stimulus and event are very important.

Learning Complex Skills

Anderson provided a major theoretical framework around the analysis of learning complex cognitive and motor skills (Anderson, 1982). He argued that the first stage of explicit or declarative learning requires the storage of the facts involved, in other words, learning the

information about 'what'. The second stage of more implicit or procedural learning, and the key to actually performing the task, requires the conversion of this information about 'what', to information about 'how'. Early efforts at execution require a careful step-by-step performance, where conscious attention is required at each step and each subsequent step has to be deliberately recalled. The final stage of learning is then the autonomous stage, where after much more practice the skill may become reflexive and no longer require any reflection. In terms of execution, the skill has moved from involving 'controlled processing' to 'automatic processing' (Shiffrin and Schneider, 1977).

Automatization

Automatization is one of the key concepts in skill acquisition and is the process by which skilled performances become smoother and smoother, requiring less and less effort, following extensive practice (Nicolson and Fawcett, 2001 - Book). In other words it is the final stage in learning any skill, where performance becomes expert and less demanding.

Automatic and Controlled Processing

Subjects can perceive, form and retrieve memories, execute certain higher cognitive functions and motor functions, all without conscious awareness. This is because with increasing practice many cognitive and motor tasks become automatic so we become less and less aware of their details. Subsequently, we seem to be unaware of the processes by which we perceive, remember, think and understand but we are aware of the products that emerge from these processes. Hence cognitive processing can be said to involve two distinct processes: automatic and controlled processing (Shiffrin and Schneider). Automatic processing requires little or no processing capacity, is rapid, involves parallel processing and is not under conscious control. Controlled processing requires a large processing capacity, is relatively slow, involves serial processing and is under conscious control. This applies to perception, memory and action.

A.2 Assessing Multi Stimulus Processing

Any information processing procedure involving two or more stimuli presented non-simultaneously is described as "sequential processing". However this includes many different processing requirements and stimulus dimensions. In an attempt to better understand the sensory data on dyslexics, it can be broken down into a logical sequence of the progressively more complex processes that might be said to fall into this rubric (Farmer and Klein, 1995). According to Hersh and Sherrick, there are at least two basic components of temporal or sequential resolution (Hersh and Sherrick, 1961).

Components of Sequential Processing

Stimulus Individuation

The first component is the introduction of a minimum time interval between two events or stimuli so that the two are 'perceived' as just barely sequential, or non-simultaneous. Determination of this minimum time has been called the separation threshold method. This aspect of temporal processing might be called 'stimulus individuation', that is, the determination of whether or not one item has been presented. Successful performance on any task involving two or more stimuli depends first on the ability to detect and perhaps identify the presence of a single stimulus. Given that such detection is within normal limits, we can then consider the various components involved in processing a sequence of stimuli. The stimuli involved may be auditory, visual or tactile, and thus the duration of the inter-stimulus interval (ISI) may be said to be an amodal property.

Detection may involve simple judgements about the presence of absence of a stimulus, or it may involve more complex judgements about the duration, location, or identity of a stimulus. The latter judgements involve discrimination in addition to detection.

Discrimination is a prerequisite for more demanding judgements (such as temporal order). Simple detection may be tested by asking a subject to report the presence or absence of a click, tone or light flash, after a cue. Variations that go beyond the simple auditory or visual detection task might involve duration judgements, like those involved in adjusting the duration of a stimulus to match the duration of a test stimulus. Location judgements might require that subjects indicate the ear to which an auditory stimulus has been presented, or localise a sound along an arc. In the visual modality, the subject might judge whether a flash has been presented

to the left or right of a fixation point. Identity can also be used as a variable; identity judgements might be made about the pitch of a tone, the colour of a light flash or the identity of a letter or digit. In such cases identity is a modality specific attribute, although identification can also involve amodal properties such as the duration of a stimulus. Tasks that involve the determination of stimulus individuation take one of several forms. Fusion tasks determine the minimum inter-stimulus interval at which the subjects are able to that there are two identical stimuli rather than one. Gap detection tasks determine the minimum ISI required for a subject to perceive that a stimulus has been interrupted by a temporal gap. Integration tasks determine the minimum ISI at which subjects perceive two non-identical stimuli, rather than one integrated form.

Temporal Order Judgement

The second sequential processing component involves a judgement of temporal order. In order for a subject to make a temporal order judgement (TOJ), the events must be identifiable as discrete elements, so that the subject is able to specify which came first. This can be done amodally by varying the location, intensity or duration or in a modality specific manner by varying the colour of light flashes in the visual modality or the frequency of tones in the auditory modality.

Sequence Discrimination

Extensions of the basic stimulus order task usually involve discrimination of stimulus sequences composed of multiple elements. That is, pairs of stimulus sequences are presented and the subjects' task is to make a same-different judgement for each pair. As in previous processing tasks, the stimulus can differ along several dimensions. Sequences may vary along the amodal dimensions of location and duration, sequences of identical stimuli, particularly visual or tactile, can be presented in various locations and, similarly, light flashes or identical frequency tones can be presented in sequences of long and short stimuli, or same length stimuli with varying intervals.

The major difference between temporal order judgement tasks previously described and sequence matching tasks is the addition of a short-term memory requirement. All matching of sequence tasks place substantial demands on memory, because the first sequence must be remembered if the second is to be compared with it.

In summary, within the broad domain of processing, the components that have been discussed and explained in some detail – perception, cognition, attention, skill acquisition and

language acquisition – are the very domains that are implicated in the various theories of dyslexia; the very domains that are the focus of this project. Hence in subsequent sections, significant references will be made to the material discussed here.

A.3 Measuring Speed of Processing

As discussed previously, an idea in cognitive neuroscience is that differences in mental ability are related to the speed of mental processing. To test this notion, a number of investigators have tried to correlate reaction time with cognitive test performance. Reaction time was a classic area for early studies, and considered a measure of the time taken by the hypothetical intervening process. According to some researchers, these reaction time measures are a way of getting at rock bottom differences in cognitive functioning, and measuring the underlying physiological processes.

Types of Reaction Time Tasks

To do an experiment one must choose a dependent variable: one must decide what to measure. The paradigm upon which the experiment is based can be inferred from the dependent variables chosen. Nowadays, measuring reaction time most often indicates a commitment to the information-processing paradigm.

The most important contribution to the study of reaction times was made by the Dutch physiologist Donders in 1868. He devised methods for studying what he called the 'Speed of Mental Processes', by distinguishing three fundamental reaction time tasks: the 'A task', 'B task' and 'C task'.

Simple Reaction Time

The 'A task' is what is now called the 'simple reaction time' (SRT) task, and has a single stimulus and a single response. Thus subject's job is merely to respond as quickly as he/she can when a stimulus appears.

Choice Reaction Time

The 'B task' is more complex, and is what is now called the 'choice reaction time' (CRT) task, and has two or more stimuli and two or more responses, with each response corresponding to a separate stimulus. The time taken to give the correct response for the stimulus presented is the choice reaction time. Thus the subject's task is again to respond as quickly as possible, but now choosing between one of several responses, depending on which stimulus is presented.

Selective Choice Reaction Time

The C task is what is now called the 'selective choice reaction time' (SCRT) task and has multiple stimuli, but only one response. One of the stimuli is the target, and requires a response, while the other stimuli do not require any reaction. Thus the subject's task is to respond as quickly as possible, but this time choosing only one specified stimulus and not the other.

Donders hypothesized that reaction time could be used to estimate the speed of internal cognitive processes. For example, he thought that the CRT involved three processes: first, the simple reaction that is, the time to respond to the stimulus; second, 'stimulus categorization' that is, the time needed to decide which stimulus had been presented; and third, response selection that is, the time needed to select the right key. Hence the choice reactions are longer than simple reaction times because two extra cognitive processes are involved. The SCRT requires the subject to make the same stimulus categorisation decisions as the CRT but does not include a response selection stage. Thus by comparing performance in these various tasks, one can obtain estimates of the time needed for the two decision processes. To find out how long it takes to categorise a stimulus, SRT is subtracted from selective CRT. Similarly response selection time can be obtained by subtracting CRT from SCRT.

Although the logic of Donders methodology has been extended, these fundamental principles still hold. Thus simple reaction time enables the measurement of speed of response and choice reaction time enables the study of decision processes. In 1885 Merkeol found that the CRT measure is sensitive to differences in high-speed processes so that the more difficult information processing takes longer. Specifically, the choice reaction time increased logarithmically with the number of alternatives.

Decomposing Mental Processes

In 1968, Smith published a remarkable integration of research on choice reaction time in which he reviewed diverse studies and fit them together. His synthesis was an information-processing framework that encompassed all disparate elements. In this framework, he conceptualised a four stage sequence of mental events intervening between choice reaction time stimulus presentation and response.

First, the raw stimulus is pre-processed, making clear representation for later processing. Second, the stimulus representation is compared with times in memory until it is categorized. Third, the categorization is used as a basis for response selection. Fourth, the subject then programs his response execution.

Smith's division of the choice reaction tasks into four discrete mental stages illustrates the essence of information processing. This task will be used in the studies undertaken in this project for this very reason: it enables the assessment of discrete components of high order perceptual and cognitive processing.

Appendix B   Methods

B.1 Subjects

Recruitment

Once the subjects agreed to participate in these studies, they were sent a letter of confirmation (B.1.1) accompanied by an information leaflet (B.1.2) and a consent form (B.1.3) for the parents to sign. These three sheets are shown below.

ADHD Screening

The parents were asked to fill ADHD Questionnaires comprising 14 diagnostic criteria for AHDH (Sheet B.1.4), from which the experimenter calculated the individual scores for each subject and mean scores for both control and dyslexic groups (Table B.1.1).

Comments on Dyslexic ADHD Scores

None of the dyslexic children scored 6 on the DSM-III R ADHD scale. In fact, only one of the dyslexics scored 4 or more. This dyslexic child has severe reading difficulties and problems with his memory and organisation.

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From: Aditi Shankardass   Direct Phone: 0114 222 6502   Email: a.shankardass@sheffield.ac.uk

Address 1

Address 2

Date Month Year

Dear

Thank you for agreeing to participate in our study. This is to confirm that your visit is fixed for:

Day, Month Date

Time

Meanwhile, please find attached the answers to some of the questions you might have about what's involved. If you need to cancel or reschedule your appointment or would like to know anything else, please feel free to contact me on 0114-222 6502.

Look forward to meeting you.

Aditi Shankardass

Event Related Brain Potentials in Dyslexics

What is it all about?

These studies are trying to unravel the mysteries of dyslexic brains and understand how the structure and function of the brains of dyslexic children is different from those of non-dyslexic children. If we know what is different, where it is different and why it is different in the dyslexic brain, this will help us to diagnose dyslexia sooner and more accurately and also help in overcoming the problems associated with dyslexia. Of course we need non-dyslexic children as well as dyslexic children, so we can find the differences and study them more closely.

What does it involve?
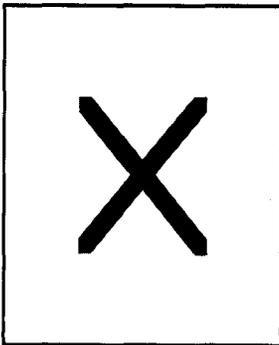
The studies generally involve recording brain activity while you view images on a computer screen and perform a task (e.g. press a button if you see a target). The measurements we take are called *event related potentials* because they are the changes in the brain's activity that occur in response to a particular event, such as your response to the target you see on the monitor. We are able to record this activity in your brain using a sensor net (see picture) which is composed of 64 sensors wrapped in small sponges and held together with elastic threads. When the net is placed on your head, the sensors sitting on the head can detect changes in your brain's electrical activity by measuring the electrical signals that the cells of the brain make as they communicate with one another.

Will it be uncomfortable?

The whole procedure is not uncomfortable at all, but the sponges are all dipped in water before the net is placed on your head so your hair will get a bit wet. So it's probably a good idea not to get a brand new hair cut before you come in for the study!

How long will it take?

Generally the studies take about 60 minutes. Occasionally the study may take longer or you may require more than one visit.

How do I get there?

We are situated in the Psychology Department of Sheffield University. If you haven't been before, I am enclosing a map with an X to mark the spot. Once you arrive go to the porter and tell him who you are and that you are here for the ERP study with Aditi. He will then let us know so we can come up and receive you.

Do I get paid?

You will be paid £5 for your time and also get a photograph of yourself with the electrode net on your head as a trophy to show your friends how you had your brain waves measured!

Do I need my parent's permission?

Since you are under 18, we prefer to have you, as well as one of your parents/guardians, sign this consent form. Please sign both copies of the form, keep one of them with you and return the other to us when you visit us.

Consent Form

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The signatures below indicate that you and your parent/guardian have read and understood the information provided and that you willingly agree to participate and that you may withdraw consent and discontinue your participation at any time.

Signature of participant   Date

_____   _____

Signature of parent/guardian   Date

_____   _____

Attention-deficit Hyperactivity Disorder Questionnaire

Date:...................   Tester:..................

Child's name:.....................................

Date of Birth:...................   Age:.........

The following questions are to assess the child's attention span and activity levels. You are asked to score the child on each of the items, by circling either a score of 1 or a score of 0.

A score of 1 is given only if the child demonstrates the behaviour at above normal levels (i.e. more than other children of their age), and the behaviour has been present at above normal levels for at least 6 months. A score of 0 is given if the child demonstrates the behaviour at normal levels i.e. the same amount as other children of their age.

Please circle the appropriate score

1	often fidgets with hands or feet or squirms in seat	Score 0 / 1
2	has difficulty remaining seated when required to do so	Score 0 / 1
3	is easily distracted by extraneous stimuli	Score 0 / 1
4	has difficulty awaiting turn in games or group situations	Score 0 / 1
5	often blurts out answers to questions before they have been completed	Score 0 / 1
6	has difficulty following through on instructions from others, not due to oppositional behaviour of failure of comprehension, e.g., fails to finish chores	Score 0 / 1
7	has difficulty sustaining attention in tasks or play activities	Score 0 / 1
8	often shifts from one uncompleted activity to another	Score 0 / 1
9	has difficulty playing quietly	Score 0 / 1
10	often talks excessively	Score 0 / 1
11	often interrupts or intrudes on others, e.g., butts into other children's games	Score 0 / 1
12	often does not seem to listen to what is being said to him or her	Score 0 / 1
13	often loses things necessary for tasks or activities at school or at home, e.g., toys, pencils, books, assignments	Score 0 / 1

14   often engages in physically dangerous activities   Score   0 / 1

Table B.1.1   Individual and Mean Scores on the ADHD Questionnaire

Name	ADHD Questionnaire Diagnostic Criteria														Sum
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	
DB															0
DT	1		1			1				1					4
JV															0
MC															0
SM															0
SB															0
TW															0
WL															0
Mean															**0.50**
JM	1		1		1	1				1		1			6
JR															0
LF			1			1							1		3
LP															0
MB										1			1		2
MC															
PG			1							1					2
TG															0
Mean															**1.85**

B.2 Experimental Design

Before the Experiment

The subjects were provided with instruction sheets to read before the experiment in order to ensure that they were prepared for the experiment in an identical fashion. The instructions sheets for the Experiment I (B.2.1) Experiment II (B.2.2), the passive (Sheet B.2.3), active (B.2.4) and familiarized (B.2.5) response conditions of Experiment III and the passive (B.2.6) and active (B.2.7) response conditions of Experiment IV are shown below.

After the Experiment

At the end of both the auditory experiments the subjects were given a set of question based upon the movie they watched during the passive and familiarized conditions, to ensure that attention was focused on the contents of the film and not the auditory stimuli being presented. The question sheets for Experiment III (B.2.8) and Experiment IV (B.2.9) are shown below.

Instructions for Experiment I

1. During this experiment you will see a shape appear on the screen in front of you every couple of seconds.

2. Most of the time this shape will be a circle as shown below. Just ignore this shape and do not respond.
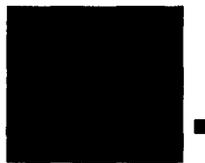
3. However, every now and then the shape will be a cross as shown below. I want you to press key 1 of the response pad every time you see this cross. Press it as fast as you can since I am recording the speed with which you react.
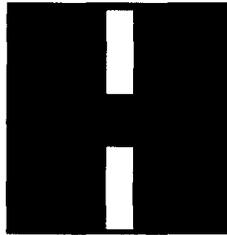

4. I will take you through a practice session before the experiment.

5. Also, try not to move about during the session. In particular, try not to move your head and shoulders because any movement that you make gets recorded by the sensors and interferes with the recording of your brain activity. I can filter out all the eye blinks that you make, so they wont interfere with the recording. But try not to blink your eyes excessively because, that gets difficult to filter out.
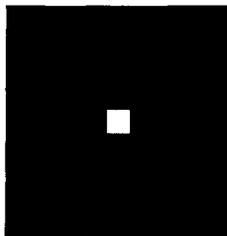
Good luck!

Instructions for Experiment II

1. During this experiment you will see a shape appear on the screen in front of you every couple of seconds. You must concentrate on the square in the centre of the screen and ignore the bars that you see above and below it.

2. Most of the time this central square will be empty as shown below. Just ignore this condition and do not respond.

3. However, every now and then the bars the square will be filled with white as shown below. Press key 1 of the response pad every time you see this filled square. Press it as fast as you can since I am recording the speed with which you react.

4. I will take you through a practice session before the experiment.

5. Also, try not to move about during the session. In particular, try not to move your head and shoulders because any movement that you make gets recorded by the sensors and interferes with the recording of your brain activity. I can filter out all the eye blinks that you make, so they wont interfere with the recording. But try not to blink your eyes excessively because, that gets difficult to filter out.

Good luck!

Instructions for Part 1 of Experiment III

1. You are about to start the first part of the experiment.

2. You will be shown a video without any sound for a few minutes, while the net on your head will record your brain activity. What I want you to do is to sit back comfortably and watch the film. Please do pay attention to what you are watching, because at the end of the entire experiment I shall ask you some questions based on what you saw.

3. Also, try not to move about during the session. In particular, try not to move your head and shoulders because any movement that you make gets recorded by the sensors and interferes with the recording of your brain activity as you watch the film. The sensors record your eye blinks but I can filter out all the eye blinks that you make, so they wont interfere with the recording. But try not to blink your eyes excessively because, that gets difficult to filter out.

4. Although you have to wear headphones as you watch the film, ignore any sounds that you might here through your earpiece during the course of the session. I just want you to concentrate on watching the film.

Good luck and enjoy the movie!

Instructions for Part 2 of Experiment III

1. You are about to start the second part of the experiment.

2. You will hear a sequence of tones from the computer. I want you to fix your eyes on the screen and listen to the tones very carefully.

3. You will hear one regular tone play every couple of seconds. Every now and then there you will hear an odd tone, which is different from the regular one. I want you to press the key 1 of the response pad every time you hear this odd one out. Press it as fast as you can since I am recording the speed with which you react.

4. I will take you through a practice session before the experiment so that you can recognise the regular tone, which you are meant to ignore and also the odd tone, which you are supposed to respond to.

Good luck!

Instructions for Part 3 of Experiment III

1. You are about to start the last part of the experiment.

2. Like the first part of the experiment, you will be shown a video without any sound for a few minutes, while the net on your head will record your brain activity. What I want you to do is to sit back comfortably and watch the film. Please do pay attention to what you are watching, because at the end of this I shall ask you some questions based on what you saw in the first part of the experiment and in this one.

3. Again, try not to move about during the session. In particular, try not to move your head and shoulders because any movement that you make gets recorded by the sensors and interferes with the recording of your brain activity as you watch the film. The sensors record your eye blinks but I can filter out all the eye blinks that you make, so they wont interfere with the recording. But try not to blink your eyes excessively because, that gets difficult to filter out.

4. As before, although you have to wear headphones as you watch the film, ignore any sounds that you might here through your earpiece during the course of the session. I just want you to concentrate on watching the film.

Good luck and enjoy the movie!

Instructions for Part 1 of Experiment IV

1. You are about to start the first part of the auditory experiment.

2. You will be shown a video without any sound for a few minutes, while the net on your head will record your brain activity. What I want you to do is to sit back comfortably and watch the film. Please do pay attention to what you are watching, because at the end of the entire experiment I shall ask you some questions based on what you saw.

3. Again, try not to move about during the session. In particular, try not to move your head and shoulders or blink your eyes excessively because any such movement gets recorded by the sensors and interferes with the recording of your brain activity as you watch the film.

4. Although you have to wear headphones as you watch the film, ignore any sounds that you might here through your earpiece during the course of the session. I just want you to concentrate on watching the film.

Good luck and enjoy the movie!

Instructions for Part 2 of Experiment IV

1. You are about to start the final part of the experiment.

2. You will hear a sequence of tones from the computer. I want you to fix your eyes on the screen and listen to the tones very carefully.

3. You will hear a pair of tones play every couple of seconds. Every now and then there you will hear an odd pair, which is different from the regular one. I want you to press the key 1 of the response pad every time you hear this odd one out. Press it as fast as you can since I am recording the speed with which you react.

4. Again, try not to move about during the session. In particular, try not to move your head and shoulders or blink your eyes excessively because such movement gets recorded by the sensors and interferes with the recording of your brain activity.

5. I will take you through a practice session before the experiment so that you can recognise the regular tone pair, which you are meant to ignore and also the odd tone pair, which you are supposed to respond to.

Good luck!

Questions on the Video Watched during the Experiment

Name: _____

The following questions are based on the comedy sketches that you just watched. For each question circle the alphabet next to the correct answer. Good luck!

1. At the bus stop, what did the lady in the queue with Mr Bean have with her?

A   A trolley

B   A pram

C   A dog

2. At the examination hall, what did Mr Bean take out of his pocket before the exam?

A   A bunch of pens

B   A pack of cigarettes

C   A photograph

3. At the beach, what did Mr Bean discover about the man sitting on the deck chair?

A   He was limping

B   He was an alien

C   He was blind

4. At the church service, what did Mr Bean use the lining of his jacket pocket for?

A   To blow his nose

B   To wipe his eyes

C   To chew on

5. At the swimming pool, what happened when Mr Bean jumped the diving board?

A   He bounced back up again

B   His trunks came off

C   He landed on a balloon

6. At the car park, why did Mr Bean wheel the rubbish bin to the car park entrance?

A   To throw his rubbish

B   To climb into and hide in

C   To somehow raise the barrier

7. At the park bench, what did Mr. Bean use to make his tea?

A   A hot water bottle

B   A kettle

C   His shoe

8. At the cinema, what sort of movie was Mr Bean watching with his date?

A   A comedy

B   A romance

C   A horror

Thank you for taking part in this experiment!

Questions on the Video Watched during the Experiment

Name _____

The following questions are based on the comedy sketch that you just watched. For each question circle the alphabet next to the correct answer. Good luck!

1. At the library what did Mr Bean do to the zipper on his pencil case?

A   He tore it off

B   He oiled it

C   He painted it red

2. At the library what did Mr Bean do when he had the hiccups?

A   He held his breath

B   He drank some water

C   He sang a song

3. At the library what did Mr Bean do when he smudged the pages in the book?

A   He poured soapy water on them to clean them

B   He told the librarian what he had done

C   He tore them out of the book and put them in his case

4. At the library what did Mr Bean do when he completely ruined the book?

A   He swapped it with the other man's book

B   He took it home with him

C   He threw it in the dustbin

Thank you for taking part in this experiment!

Appendix C   Results

All auditory stimuli of a duration less than ~100 ms appear to be delayed by 100 ms resulting in a latency shift of 100 ms in the resultant ERP trace. In the AS study, this effect was seen in the standard stimuli of all the pitch and duration conditions (all of 50 ms duration) tones, as well as the target tones in the easy and hard pitch (both 50 ms long) and hard duration (75 ms long) condition.. In the AC study this effect is seen in the standard and target stimuli of the fast speed condition (both of 100 ms duration) but not in the standard and targets of the slow speed condition (both of 250 ms duration).

The source of this problem was still being determined at the time of writing this thesis. However, since the ERP analysis was based upon the 'waveform-based' and 'process based' convention (see Section 1.3.3 for an explanation), each wave component was identified on the basis of these criteria. Since the latency shift occurred with both dyslexic and control groups, this meant that all comparisons were made on the same waveform regardless of the time of its occurrence and there were no internal errors in the analysis.

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