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**SENSORY PROCESSING
IN DYSLEXIC CHILDREN**

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Submitted in fulfilment of the requirements of Doctor of Philosophy

March 2005

Abstract

This study tested the prediction that a group of dyslexic children ($n = 70$) would be less sensitive to auditory and visual temporal stimuli than a control group ($n = 52$). In the auditory domain, detection thresholds for 2 Hz FM, 2 Hz AM and 20 Hz AM were assessed. The modulations in these stimuli are detected on the basis of temporal cues. In contrast, the modulations in the control stimulus 240 Hz FM modulate too rapidly to be detected with temporal cues. The dyslexic group were significantly less sensitive than the control group to the temporal and non-temporal measures at initial testing (Phase 1) and again nine months later (Phase 4). These data demonstrated that the auditory deficit in the dyslexic group was more general in nature than had previously been suggested. In the visual domain, sensitivity to global coherent motion was assessed. The dyslexic group were significantly less sensitive than the control group on this measure at both phases of the study.

Despite the overall between group differences, the magnitude of the effects were low to moderate. There was also substantial overlap between the performance of the two groups on the sensory processing measures. A deviance analysis was conducted to determine the proportion of dyslexic individuals who had sensory processing deficits. When data from each phase was examined separately, the incidence of sensory processing deficits in the dyslexic group was comparable to previous studies. However, when the data from both phases was combined, only 5-18% of the dyslexic group had impairments on any of the sensory tasks that were stable across time. Nevertheless, these results do not preclude sensory processing making a contribution to reading difficulties in some children. When the relationship between sensory processing thresholds and reading ability was considered, sensitivity to auditory and visual temporal measures accounted for significant unique variance in phonological

processing, orthographic coding and overall reading skill, even after accounting for IQ and vigilance.

This study was also tested the prediction that visual attention can explain the link between visual temporal processing and reading. Vidyasagar (1999) proposed that the magnocellular (M) system, which processes temporal stimuli (e.g., motion), is also important for efficient functioning of an attentional spotlight. This spotlight is proposed to arise in parietal cortex (a major endpoint of the M system), and is involved in highlighting areas for detailed visual processing when performing visual tasks, such as visual search or reading. It was predicted that only those dyslexic participants with motion detection impairments would also be impaired on a serial search task that required the attentional spotlight. On average, the dyslexic group had significantly slower serial search than the control group. However, the magnitude of effect was small and a deviance analysis demonstrated that only 8.5% of the dyslexic group had stable impairments relative to the control group. Furthermore, only one of the six dyslexic participants with a visual attention impairment had a co-existing deficit in detecting coherent motion. Thus, visual attention deficits of this type appear to exist independently of coherent motion deficits.

This study also provided important evidence on the reliability of measurement for the sensory processing tasks. The data showed that the test-retest reliability of the sensory measures was only moderate over a nine month period. Test-retest for other cognitive measures over the same time frame was high - including that for an orthographic coding task, which had similar procedure and task demands to the sensory measures. The results also demonstrated that a high proportion of participants in both groups performed inconsistently across time (i.e., they had a threshold indicative of a deficit at one phase and performance within normal limits at the other). Up to 32% of the dyslexic group and 19% of the control group had inconsistent performance on the

sensory measures across time. The importance of developing more reliable methods of estimating sensory sensitivity is discussed, as is the need for normative data on sensory processing tasks in order to more accurately make decisions about the incidence of sensory deficits. In summary, this study provided evidence for a relationship between sensory processing and reading. However, the current data demonstrated that sensory processing deficits are not characteristic of all dyslexic individuals. Future research should focus on explaining why only a sub-group of dyslexics have sensory deficits, and also why some control participants have deficits.

Declaration

I declare that this work has not previously been submitted for a degree or diploma in any university. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made in the thesis itself.

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Craig Wright

March 2005

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1.0 Reading and Dyslexia

1.1 Introduction

Dyslexia occurs in 5-10% of the population (Yule, Rutter, Berger & Thompson, 1973) and has its most salient effect on reading (Frith, 1997). Since 1980, a large body of research has been devoted to identifying the neurological mechanisms in the auditory and visual systems that underlie dyslexia. In general, this research has found that dyslexic groups are less sensitive than controls to specific types of temporal auditory and visual stimuli (e.g., Hansen, Stein, Orde, Winter & Talcott, 2001; Witton, Stein, Stoodley, Rosner & Talcott, 2002). Significant relationships have also been observed between sensitivity thresholds for auditory and visual sensory stimuli and reading skills (e.g., Talcott et al., 2002; Witton et al., 2002). Although promising, a number of failures to replicate (e.g., Hari, Saaskilahti, Helenius & Uutela, 1999; Hill, Bailey, Griffiths & Snowling, 1999; Kronbichler, Hutzler & Wimmer, 2002) have meant that the reliability of these research results is yet to be completely established. Two methods can be used to investigate the reliability of research results. The first is to directly replicate previous methodology (external replication). The second is to replicate methodology and results within the same group of participants at different points in time (internal replication; Ives, 2003). One aim of the current study was therefore to replicate the results of a number of recent investigations – both externally and internally.

A criticism that could be made of a lot of research, including that investigating sensory processing research in dyslexia, is that there has been an over-reliance on interpretation of statistical significance testing (e.g., p values) when reporting results. The most frequently expressed concern about statistical significance testing is that the p value depends essentially on two things: the size of the effect and the size of the sample

(e.g., Carver, 1993). It is possible to get a significant result either if the effect were very big (despite having a small sample) or if the sample were very big (even if the actual effect size were small; Biskin, 1998; Plucker, 1997). While it is important to know the statistical significance of a result, a significant p value does not describe the magnitude of the effect, or the practical significance of a result (e.g., Cohen, 1992; Vacha-Haase & Thompson, 2004). Thus, many studies may report statistically significant results, even though the magnitude of the effect has little practical value (Ives, 2003). Alternatively, a large effect may be trivialised when a study with low power based on small sample size reports a non-significant p value. To avoid this problem, strong recommendations have been made for inclusion of effect size data to measure the practical meaningfulness of studies in which p values are used (Wilkinson & APA Task Force on Statistical Inference, 1999). This allows for a direct comparison of the size of the effect across studies, that is independent of the sample size. Within the dyslexic literature, only a small number of the most recent studies have reported effect size data (e.g., Conlon, Sanders & Zapart, 2004; Witton et al., 2002; Wilmer, Richardson, Chen & Stein, 2004). In the review to be presented below, the effect sizes reported by these authors are presented. Where possible, the author of the present study has also calculated effect sizes from previous studies that have not explicitly reported them in the text. By focusing on measures of practical as well as statistical significance, the present study will assist in the development of knowledge about sensory processing in dyslexia. Comparing the effect sizes generated in the present study to those reported by previous research, as well as determining if the magnitude of effects can be replicated internally across time, this study will also provide useful information on the reliability of measurement of the visual and auditory tasks used. In addition, the current study aimed to determine the test-retest reliability of a number of auditory and visual temporal processing tasks that are currently in widespread use (Talcott, 2004). To the author's

knowledge, no study to date has investigated this issue.

Although auditory and visual processing deficits have been found in dyslexic groups, the extent to which these impairments are a defining characteristic of dyslexics is unclear. Therefore, in addition to investigating the statistical significance and practical meaningfulness of results at a between groups level, the current study will use the same technique employed by Ramus et al. (2003) to determine the proportion of individuals within the dyslexic group with sensory processing deficits. A further challenge for researchers is to investigate the characteristics of those individuals who display sensory processing deficits. A number of hypotheses have been put forward to meet this challenge. For example, some studies have proposed deficits only exist in a particular sub-type of dyslexia (e.g., Slaghuis & Ryan, 1999; Borsting et al., 1996). Other studies have suggested sensory deficits exist only in dyslexics with a co-existing oral language disorder (Heath, Hogben & Clark, 1999), while others have argued the deficits observed are the result of inattention in dyslexics while performing psychophysical tasks (Roach, Edwards & Hogben, 2004; Stuart, McAnally, & Castles, 2001). The current study considered an alternative hypothesis. Clay (1987) has argued that almost all studies investigating the underlying neurological mechanisms in dyslexia may have been confounded by the failure to control for environmental factors, such as lack of exposure to text or inappropriate reading instruction. That is, by failing to control for these environmental factors, many studies may have included individuals in dyslexic groups who had reading problems, not as a result of impairments in basic neurological mechanisms, but because of environmental factors. This study predicted that this methodological issue could explain why studies typically find only a sub-group of dyslexics have sensory impairments, and even why some studies fail to find sensory deficits at all. Therefore, the current study re-investigated sensory processing after controlling for the educational history of the children in the dyslexic group by re-

evaluating their reading skills after they had been engaged in nine months of school-based reading intervention.

The evidence upon which these hypotheses are based will be examined in the following chapters. The review will begin by addressing a number of important definition and measurement issues relating to reading and dyslexia. Chapter 2 will discuss the evidence for temporal auditory processing deficits in dyslexia, while Chapter 3 will focus on the evidence for visual temporal processing deficits in dyslexia. Both Chapters 2 and 3 will also discuss the relationships that are hypothesised to exist between auditory and visual processing and reading skills. Chapter 4 will then examine visual attention as the possible link between visual temporal processing deficits and dyslexia. Finally, Chapter 5 will provide a brief summary of the relevant literature and discuss the current study in greater detail.

1.2 Definition and Measurement Issues

Any discussion of reading and dyslexia must be preceded by an overview of several basic measurement and definition issues. The first of these is how reading is defined and measured. Throughout the literature, reading skills have been measured in two quite different ways: reading comprehension and word decoding. Reading comprehension tests typically involve the reading of text passages followed by questions about the text. Tests of word decoding require the reader to identify single words. Although comprehension is clearly a fundamental goal of reading, its measurement is difficult and can be confounded by a number of processes such as background knowledge, general language skills and reading speed (Siegel, 1993). In contrast, tests of word decoding measure more basic processes and do not suffer the same problems of confounding variables as reading comprehension measures (Siegel, 1993).

Furthermore, efficient word decoding skills are fundamental to comprehension of written text (Gough & Tunmer, 1986; Stanovich, 1982a; 1982b) and the ability to identify isolated words is significantly related to the ability to extract meaning from text (Shankweiler & Liberman, 1972). The primary difficulty for the beginning reader and for dyslexic children is in developing word-level decoding skills, which in turn interferes with reading and comprehending connected text (Shankweiler & Liberman, 1972). As word decoding is central to the reading process (Siegel, 1993; Vellutino, Scanlon & Tanxman, 1994) and is the primary behavioural difficulty in dyslexic children, this review will focus on evaluating the cognitive abilities underlying that skill.

1.3 Terminology

A central issue in the area of dyslexia research involves the appropriate terminology to describe reading difficulties. The terminology used to describe reading difficulties in the literature is inconsistent. The fourth edition of the Diagnostic and Statistical Manual of Mental Disorders (DSM-IV; American Psychiatric Association, 1994) uses the term reading disorder. Some studies use the term reading disability (e.g., Joshi, 2003; Vellutino et al., 1996), while others have used the undifferentiated label of learning disability (e.g., Sternberg & Grigorenko, 2002). Problems exist in the use of each of these terms. For example, reading disorder, like the term mood disorder, implies an aberrant pattern of thinking or behaving that requires some form of intervention before the individual can function 'normally'. The term reading disability implies a global impairment that affects all areas of functioning (Snowling, 2000) and use of the undifferentiated term learning disability fails to specify the child's difficulties and implies global impairments. In this study, the term dyslexia will be used. It needs also to be noted that dyslexia exists across cultures and different language systems.

However, the present study will confine discussion to dyslexia as it exists within the English language.

1.4 Definitions of Dyslexia

Dyslexia is typically defined as severe difficulty in developing reading skills in children of at least average intelligence who are not otherwise impaired by more general learning difficulties, such as low IQ or receptive or expressive language impairment (Stanovich, 1988; Vellutino et al., 1996). The aetiology of dyslexia is assumed to have a biological basis, such as a genetic limitation or genetic disorder, which adversely affects the cognitive abilities underlying reading (Vellutino et al., 1996). Common definitions of dyslexia include a number of exclusionary criteria which define factors to aid in distinguishing between children whose reading problems are caused mainly by environmental and experiential factors, and children whose reading problems are caused by biological factors. These exclusionary criteria are typified in the following definition of dyslexia from the World Federation of Neurology (Critchley, 1970. p. 11). Dyslexia is:

A disorder manifested by difficulty in learning to read despite conventional instruction, adequate intelligence and socio-cultural opportunity. It is dependent upon fundamental cognitive disabilities which are frequently of constitutional origin.

The definition by exclusion, as it has become known, has been criticised for only describing what a dyslexic can not be and for not providing positive criteria for diagnosis (Snowling, 2000). A number of the terms are also ill defined. For example, what constitutes adequate intelligence and what is involved in conventional instruction (Snowling, 2000)?

An alternative to the exclusionary model is to define dyslexia using discrepancy criteria. Discrepancy definitions symbolise the idea that dyslexia occurs in the absence

of a global deficit in cognitive function (Bishop & Snowling, 2004) and are typified by the diagnostic criteria contained in the DSM-IV (American Psychiatric Association, 1994). The DSM-IV requires a discrepancy between performance on a standardised test of reading ability and a test of IQ for diagnosis. The use of the discrepancy definition is in widespread use, mainly because of the popularity of the DSM-IV among health professionals and because the discrepancy definition is enshrined in the legislation of many US states. However, a number of problems with the use of the discrepancy method have been identified.

For example, IQ scores (particularly verbal IQ) are problematic because they are confounded with reading scores (Sternberg & Grigorenko, 2002), most probably due to the fact that items on verbal IQ sub-tests often involve reading material, knowledge obtained through reading or other verbal material. Stanovich (1986) has also pointed out that a Matthew effect is involved in the relationship between reading and verbal IQ. The Matthew effect is a biblical reference to the rich getting richer and the poor getting poorer. Stanovich (1986) contends skilled readers are in a better position to expand their vocabulary and verbal knowledge through reading, and thus perform better on IQ tests. The effect on students with dyslexia may be the opposite. Reading difficulty, possibly coupled with an aversion to reading, may lead to poorer performance on IQ tests, thus reducing the chance of identifying a discrepancy between IQ and reading achievement.

In an attempt to avoid this problem, some psychologists have employed non-verbal tests of ability, which typically contain more limited language demands. However, the use of non-verbal IQ scores is also problematic, not least because they are a poor correlate of reading (Bishop & Snowling, 2004). In fact, IQ scores can account for no more than 25% of the variance in reading ability, particularly in young children (Joshi, 2003), while other studies have shown the correlation co-efficients between IQ

and reading scores for the first three grades of only ~ 0.4 (see Stanovich, Cunningham & Freeman, 1986).

Discrepancy scores are also subject to a statistical artefact known as statistical regression to the mean. Regression to the mean refers to the phenomenon that when prediction is less than perfect (as in IQ and reading achievement), predicted outcomes are likely to move towards the mean on a repeat testing (which is rarely conducted for clinical or research-based diagnosis of dyslexia). The greater the departure of the reading scores from the mean, the greater the amount of statistical regression (Sternberg & Grigorenko, 2002). As discrepancy definitions are typically based on very low reading scores they are susceptible to error, possibly leading to misdiagnosis of dyslexia.

Another problem for the discrepancy definition is that few differences appear to exist between individuals with reading difficulties who meet discrepancy definition criteria and individuals with reading difficulties who do not meet discrepancy criteria, but who did not have an intellectual impairment (backward readers). Discrepancy defined and backward readers exhibit little difference in terms of their cognitive and behavioural reading profile and current evidence also suggests both discrepant and non-discrepant poor readers benefit from the same type of reading instruction. There is also no evidence to support the assumption that discrepancy defined poor readers obtain greater benefit from reading instruction (e.g., Fletcher et al., 1994; Siegel, 1988; Stanovich, 1991; Foorman, Francis, Fletcher & Lynn, 1996; Francis, Fletcher, Shaywitz, Shaywitz & Rourke, 1996; Vellutino, Scanlon & Lyon, 2000).

Perhaps because of the controversial nature of discrepancy-based definitions, the tradition in the field of reading research has been to identify a mismatch between chronological age and reading age (e.g., Lovegrove, Bowling, Badcock & Blackwood, 1980; Slaghuis & Lovegrove, 1993; Williams, Stuart, Castles & McAnally, 2003). A

reading age is a derived score, which estimates the age at which a given raw score on a reading test is average or typical. The use of reading age scores has led to comparisons of groups of dyslexic or poor readers who differ substantially in severity. For example, Slaghuis and Lovegrove (1984) used readers with a mean reading delay of 3 years and 10 months, Lovegrove et al. (1980) tested children with a reading delay of 5 years, while Williams et al. (2003) tested children with a mean reading delay of 18 months.

The problem of how to define dyslexia is therefore a contentious issue in the literature (Bishop & Snowling, 2004; Siegel, 1988; Stanovich, 1991; Vellutino et al., 2004) and many researchers have now chosen to reject discrepancy criteria in favour of a low achievement definition which also sets limits for degree of reading impairment and intelligence. Such a definition typically involves an IQ of > 90 and reading ability below the 15th percentile. In research, the use of intelligence tests is not excluded because cognitive ability could well affect performance on the experimental cognitive and sensory tasks upon which the participants are typically assessed. It is therefore considered important to compare dyslexic and skilled readers who do not differ in intelligence.

The use of a low achievement definition with set limits for IQ is also not without its problems. Most notably, the use of such criteria may lead to obtaining a heterogeneous group of children, including some who would not normally receive clinical attention, and some who have co-existing global language disorders (Bishop & Snowling, 2004). Another problem with the use of a low achievement definition is that reading ability constitutes a normal distribution, with poor reading (and dyslexia) simply existing at the lower end of that distribution (Fletcher et al., 1994; Shaywitz, Holohan, Fletcher & Shaywitz, 1992; Stanovich & Siegel, 1994). Any cut-off point for degree of reading difficulty is therefore arbitrary.

Despite the inherent problems with using arbitrarily created groups, this study followed recent convention (e.g., Kronbichler et al., 2002; Vellutino et al., 1996; Williams et al., 2003), and initially adopted a low achievement definition of dyslexia by setting limits for degree of reading impairment and intelligence. Participants were classified as dyslexic if they were of at least average intelligence, with a lower limit of 90 on a standardised non-verbal test of ability (Raven, Court & Raven, 1995), and scored below the 15th percentile on a combined measure of word decoding skill (Woodcock, 1997). Skilled readers were required to score at or above the 40th percentile on the same reading measures. The 15th and 40th percentiles was selected in order ensure adequate separation between the groups of dyslexic and skilled readers.

4 Individual Differences in Dyslexia

Another issue relevant to the definition of dyslexia is whether dyslexic children can be separated into subtypes. One technique that has been used in the reading literature has been to make a distinction between phonological and surface dyslexia (Bishop & Snowling, 2004). In phonological dyslexia, children can read words, but typically have difficulty applying phonological decoding skills when reading nonwords. In surface dyslexia, children are typically able to read nonwords and regular words using phonological decoding skills. However, they have difficulty distinguishing between homophones like pair-pear, their spelling is phonetic (e.g., school → skool) and they have difficulty reading exception words, such as 'yacht', which cannot be accurately decoded (Castles & Coltheart, 1993; Snowling, 2001).

Although the existence of distinct subtypes of dyslexia remains the subject of some debate, research has demonstrated little support for the concept of subtypes. For example, Manis, Seidenberg, Doi, McBride-Chang and Petersen (1996) demonstrated that children with a phonological profile, had significantly lower levels of phonological

skill than both chronological and reading age matched controls. In contrast, children with a surface profile performed at a similar level to reading age matched controls on tasks of phonological skill. Stanovich, Seigel and Gottardo (1997) also found similar results. The results of these studies have been interpreted as showing that dyslexic children with phonological deficits have a 'disorder of development', whereas children showing a surface profile represent a developmental delay.

The definition of dyslexia employed can also affect conclusions regarding the existence of subtypes (Siegel, 1993). For example, Siegel and Ryan (1989) demonstrated that if dyslexia is defined as a deficit in single word decoding skills, children with reading difficulties constitute a homogenous group. In contrast, if dyslexia is defined as a deficit in reading comprehension, the group that emerges is heterogenous and may be subject to subtyping. Thus, as Siegel (1993) has argued, when subtypes emerge they may be artefacts of the definition used in a particular study.

A third important variable for the reading profile of dyslexics may be the type of reading instruction they receive. Thomson (1999) studied the surface errors, such as regularising exception words (reading come as kome) and phonetic spellings (wayt for wait) of dyslexic children who were enrolled in a special school where there was a structured multi-sensory phonics approach to teaching. The children received explicit instruction in developing sound-letter links and mapping sounds onto orthographic knowledge (Thomson, 1999). After two years of this instruction, it was shown that the prevalence of errors characteristic of a surface dyslexic, such as regularising words and using phonetic spellings increased significantly. These results demonstrate that appropriate reading instruction designed to remediate the primary phonological and decoding problems that are experienced by dyslexics can create the profile of a surface dyslexic.

A Basic Cognitive Processes Underlying Reading

Siegel (1993) has postulated that five basic processes are involved in the development of written language skills (reading). These five processes involve phonology, syntax, working memory, semantics and orthography (Siegel, 1993). Two of these processes, phonology and orthography, are important for this study and will be reviewed in detail below.

4 Phonological processing

Current theories of reading (e.g., Adams, 1990; Byrne, 1998; Ehri, 1995; Frith, 1985; Share, 1995) argue that phonological processing is the most important cognitive variable underpinning reading development. A deficit in phonological processing is also thought to lie at the core of dyslexia (Stanovich, 1988). At least three components of phonological processing have been identified: phonological awareness, phonological memory and rapid naming. The importance of each process to reading and how a deficit can lead to dyslexia will be reviewed in the following sections.

F Phonological awareness

Phonological awareness refers to the ability to reflect explicitly on the different units of sound that comprise spoken language (Lundberg, 2002; Snowling, 2000; Wagner, Torgesen & Rashotte, 1999). It develops in stages from the global to the specific. In early development, children are only aware of word-length phonological units, such as recognising the two parts of the compound word cow-boy. They then develop an understanding of syllables within words, as in recognising the two syllables in the word seven. Awareness then proceeds to recognition of onset and rime within a syllable. For example, in the single syllable word sit, the onset is the sound of the initial

‘s’, and the rime is the sound of the vowel and remaining consonant ‘it’. Eventually, awareness is developed for individual phonemes within words. For example, the word sit is comprised of the phonemes represented by the letters ‘s’, ‘i’ and ‘t’ (Wagner et al., 1999).

The importance of phonological awareness to reading has been supported by research which has demonstrated that early phonological skills are significant predictors of alphabetic knowledge and later reading skill (e.g., Bradley and Bryant, 1983; 1985; Foorman, Francis, Novy & Liberman, 1991; Liberman, Shankweiler, Fischer & Carter, 1974, Lundberg, Olofsson & Wall, 1980, Muter, Hulme, Snowling & Taylor, 1998; Stuart, 1995; Vellutino & Scanlon, 1987; Wagner, Torgesen & Rashotte, 1994; Wagner et al., 1997). Intervention studies that report gains in reading skill following phonological training also support the importance of phonological skills to reading (e.g., Ball & Blachman, 1991; Bradley & Bryant, 1983; 1985; Felton, 1993; Foorman, Francis, Fletcher, Schatschneider & Mehta, 1998; Hatcher, Hulme & Ellis, 1994; Iversen & Tunmer, 1993; Torgesen, Wagner & Rashotte, 1997; Vellutino et al., 1996). A large body of research has also demonstrated that dyslexics have phonological awareness deficits when compared to skilled readers (e.g., Bradley & Bryant, 1978; Bruck, 1992; Fox & Routh, 1980; Holligan & Johnston, 1988; Rack, 1985; Swan & Goswami, 1997; Vellutino & Scanlon, 1987; Vellutino et al., 1996).

The dominant interpretation of this research is that phonological awareness plays an important role in development of word-level decoding skills. It is thought to aid the beginning reader develop knowledge of the alphabetic principle, which underlies efficient word decoding (Byrne & Fielding-Barnsley, 1989). The alphabetic principle refers to an understanding of how specific phonemes in speech are represented by specific orthographic units (written letters; Byrne & Fielding-Barnsley, 1989).

Alphabetic knowledge allows the child to decode words that have letters in common.

For example, knowing the letter string pat makes the sounds /p/ /a/ and /t/ and that the letter string sit makes the sounds /s/ /i/ and /t/ allows the reader to make the abstraction to the new words sat and pit. In addition to reducing the load on visual memory, alphabetic knowledge helps bring the orthographic regularities and redundancies in written English to the child's attention and allows them to operate as an independent reader (Share, 1995; Vellutino et al., 1994).

Understanding how phonological awareness develops in children has allowed researchers to develop tools to measure phonological awareness at different developmental stages. Typical syllable awareness tasks include items on which the child is required to blend orally presented syllables to form a word (e.g., win-dow becomes window). Onset-rime tasks follow a similar format in which blending of the onset and rime of a spoken word is required (e.g., s – it becomes sit). Onset-rime awareness is also commonly measured using a rhyme oddity test in which the child has to select the word that does not rhyme from a group of three orally presented words (e.g., dog pot log).

Phoneme awareness can also be assessed with blending tasks in which the child is required to blend a string of orally presented phonemes to form a word (e.g., s – i – t becomes sit). More difficult phoneme awareness tasks include measures of segmentation ability, in which the child is required to segment a word into its constituent phonemes (e.g., sit becomes s – i – t), phoneme elision, in which the child has to delete a phoneme from an orally presented word to form a new word (e.g., igloo without the ll becomes igoo), and spoonerisms, in which the child has to transpose the first letters of two orally presented words (e.g., Michael Jackson becomes Jikal Mackson).

Although the dominant view, as outlined above, is that phonological awareness precedes reading and has a causal effect on development of alphabetic skills, there are

other ways of interpreting the correlational relationship (see Castles & Coltheart, 2004 for review). One explanation is that it is the process of learning to read itself that alerts the beginning reader to the phonological segments in spoken language (e.g., Ehri, 1989, Morais, 1991). A related explanation is that the development of reading skills does not actually change the level or nature of phonological awareness itself. Instead, it affects the way individuals perform phonological awareness tasks (Castles, Holmes, Neath & Kinoshita, 2003). These authors argue that as alphabetic skills develop, phonological awareness tasks can increasingly be performed using orthographic knowledge rather than purely phonological information. There is certainly some evidence to support this theory. For example, Stuart (1990) found that when asked to delete the sound /n/ from a word like *bind*, children were just as likely to produce an orthographically-based response that changed the vowel sound (“*bid*”) as they were to produce a phonologically-based response (“*bide*”).

Although there is some controversy regarding the nature of *phonological awareness* tasks, the convention within the literature is to accept that the tasks outlined above are measuring phonological skills. This study will follow that convention. Furthermore, the major purpose of this study is to replicate previous studies (e.g., Talcott et al., 2002; Witton et al., 2002) that have used similar tasks and labelled them *phonological awareness* tasks.

} *Phonological memory*

Phonological memory refers to the ability to code information in a temporary storage in working memory. The part of memory involved in short term storage of phonological information is referred to as the phonological loop (see Baddeley, 1986; Baddeley & Hitch, 1974; Gathercole, 1999). The phonological loop holds information in terms of its sound structure or phonology (Baddeley, Thomson & Buchanan, 1975).

Phonological information is held in a short-term store, where it is subject to rapid decay (~2 sec). Sub-vocal rehearsal facilitates more detailed processing by offsetting decay of the information by refreshing the phonological traces (Pickering & Gathercole, 2001). A typical test of phonological memory involves repeating series of orally presented digits of increasing length, or repeating a series of nonsense words.

A number of studies within the last twenty years have demonstrated that dyslexics perform more poorly than skilled readers on these types of tasks, indicative of phonological memory impairments (De Jong, 1998; Gathercole & Pickering, 2000; 2001; Paulesu et al., 1996; Shankweiler et al., 1979; Vellutino et al., 1996).

Phonological memory does not impair reading or listening to any great extent, providing the words involved are already in the reader's vocabulary. However, phonological memory impairments can constrain the ability to learn new written and spoken vocabulary (Gathercole & Baddeley, 1990; Gathercole, Service, Hitch, Adams & Martin, 1999; Torgesen, 1996). Phonological memory is involved when the reader attempts to decode new words, particularly long words, as a means of storing intermediate sounds prior to blending (Wagner et al., 1999). Phonological memory is also significantly related to the ability to learn letter names in children (de Jong & Olson, 2004).

Rapid naming

Rapid naming refers to the ability to efficiently retrieve the phonological label associated with digits, letters or familiar objects from long-term memory. A typical task requires the child to name a grid of twenty familiar objects as quickly as possible. Dyslexics perform rapid naming tasks more slowly than skilled readers (Felton & Wood, 1989; Katz, 1986; Pennington, Orden, Smith, Green & Haith, 1990; Snowling, van Wagendonk & Stafford, 1988; Swan & Goswami, 1997; Vellutino et al., 1996; Wolf, 1986). Rapid naming taps speed of phonological processing or phonological access (Snowling, 2000; Wagner et al., 1999) and has therefore been linked to reading fluency. Poor rapid naming ability may also mark a deficit in the rate of learning (Torgesen & Davis, 1996).

F Dyslexia: A Deficit in Phonological Representations

One current explanation for the range of phonological difficulties dyslexics experience is that they have difficulties in establishing, and later accessing, well specified phonological representations (Fowler, 1991; Snowling & Hulme, 1994; Swan & Goswami, 1997; see Snowling, 2000 for a review). Phonological representations are essentially memory 'codes' of the 44 phonemes in the English language. It is proposed that, when young, dyslexics have subtle speech perception deficits, which interfere with the ability to adequately specify phonological representations (Snowling, 2000). The advantage of this hypothesis is that it can account for a wide range of behavioural difficulties that dyslexics experience and it also makes sense in terms of what is known about the development of reading. The second component of reading ability that is relevant to the present study is orthographic coding. The role that orthographic skill plays in reading and in dyslexia will be reviewed in the following section.

o Orthographic Coding

Orthographic coding refers to the ability to represent the unique array of letters that defines a printed word (Huslander et al., 2004; Vellutino et al., 1994). It has also been defined as the ability to use familiar orthographic sequences to access the lexicon without phonological mediation (Olson, Forsberg, Wise & Rack, 1994). Orthographic coding may be particularly important for word identification in the English language because, in printed English, many words do not lend themselves to application of alphabetic decoding skills. These words are typically referred to as exception words (e.g., island, pint and lieutenant). Orthographic coding ability as a cognitive process depends upon aspects of the visual system including: visual feature analysis, attention to visual detail, and visual pattern analysis (Vellutino et al., 1994).

There are currently no standardised measures of orthographic coding ability, nor does there appear to be any consensus on an optimal measure (Olson et al., 1994; Vellutino et al., 1994). The reading of exception words has been a popular method of measuring orthographic coding within the literature. The rationale for using exception words is that they violate regular sound-letter rules, which underpin phonological decoding. Exception words are therefore presumed to be read directly, based on the participant's memory for the specific orthographic form of that word (Coltheart, 1978; Olson et al., 1994). However, for the participant to have opportunity to code the orthographic features of a word, they must have had prior exposure to that word. Exception word reading may therefore be confounded by exposure to print.

Many exception words can also be at least partly decoded on the basis of regular sound-letter rules (e.g., answer). Thus, successful performance on an exception word reading task may be aided by phonological processing (Olson et al., 1994). Other tasks have attempted to remove the effects of phonological processing skill. For example,

many studies have employed a modified lexical decision task in which participants view a word (e.g., take) and a pseudohomophone that has identical phonological output (e.g., taik). The participant is required to select the “real word”. In general, these types of tasks continue to account for significant portions of the variance in word identification skill after removing variance accounted for by phonological processing skill (Vellutino et al., 1994). Although this has been accepted as evidence for an independent contribution of orthographic coding facility to word identification skill (e.g., Olson et al., 1994), others have argued that the evidence for the independence of orthographic coding from linguistic systems, such as phonology and semantics is minimal (Manis, Custodio & Szeszulski, 1993; Seidenberg & McClelland, 1989; Snowling, Goulandris & Defty, 1996; Snowling, Hulme & Goulandris, 1994; Vellutino et al., 1994).

Dyslexic children also perform more poorly on measures of orthographic coding ability, such as the pseudohomophone task, than age matched control children (e.g., Manis, 1993; Olson, Kliegl, Davidson & Foltz, 1985; Olson et al., 1993). However, they perform at a similar level (Manis, 1993; Olson et al., 1994) or better (Olson et al., 1995) than reading age matched control children. One explanation for the difficulty that dyslexic children have in orthographic task performance is therefore that they have less exposure to text because of lower overall reading or spelling ability, rather because they have impairments in basic orthographic processes (Vellutino et al., 1994).

n Summary

There has been considerable controversy as to what constitutes an appropriate definition of dyslexia. Both the exclusionary and discrepancy approaches have significant problems that have been discussed in this chapter. For the purposes of this research study dyslexia has been defined simply as low reading achievement (< 15th percentile) on a measure of word decoding. Children with an IQ of < 90 were excluded

from the sample because cognitive ability could affect performance on the sensory processing tasks to be administered.

The primary behavioural deficit in dyslexia in children is in word-level decoding skills; a problem that has been associated with impairments in phonological processing. In contrast, problems with basic orthographic coding do not appear to be a primary cause of reading difficulty in dyslexic children. At a cognitive level, problems with phonological processing have been linked to difficulty establishing, and later accessing phonological representations (Fowler, 1991; Snowling & Hulme, 1994; Swan & Goswami, 1997). However, the neurological cause of these cognitive and behavioural deficits are yet to be established. The following chapters will examine the evidence for auditory and visual sensory processing deficits in dyslexics, which have been linked to reading difficulties.

t Auditory Processing and Dyslexia

In Chapter 1 it was established that a number of cognitive variables, particularly phonological processing, are strongly associated with reading and dyslexia. What is less clear is the neurological basis of the cognitive deficit in phonological processing. One explanation for phonological impairments is that problems with phonology can be traced to low-level auditory deficits, which affect the quality of the speech signal reaching the auditory cortex and subsequent language areas (Goswami et al., 2002; Richardson, Thompson, Scott & Goswami, 2004; Tallal, 1980; Witton et al., 2002). The deficit implied here is not the result of peripheral hearing loss, but one that involves the central auditory processing systems, typically occurring in the presence of a normal audiogram.

Prior to examining the hypothesis in more detail, it is important to distinguish between two basic processes that are often confounded in the literature: that is, temporal processing, which refers to perception of the temporal properties of events (e.g., duration, sequence, relative timing, rhythm), and judging the temporal order or discriminating between stimuli that are presented at rapid rates (i.e., processing of rate). Only the former can be properly considered “temporal perception”. Difficulties in identifying or discriminating brief stimuli separated by brief intervals indicate a deficit in rapid auditory processing, not a deficit in temporal perception (Mody, Studdert-Kennedy & Brady, 1997). A distinction will therefore be made in the following review between rapid auditory processing and temporal processing. While temporal processing in dyslexia is of greatest interest for the current study, the evidence for a rapid auditory processing deficit will be presented first to provide a historical overview of the auditory processing research in dyslexia.

s **Rapid Auditory Processing Deficits in Dyslexics**

Development of the rapid auditory processing theory was based on the work of Paula Tallal and colleagues using children with specific language impairments (SLI). SLI is defined by a specific deficit in oral language skills in the presence of otherwise intact cognitive abilities (Rosen & Manganari, 2001). In a series of studies Tallal and Piercy (1973a; 1973b; 1974; 1975) compared SLI children with controls on the Auditory Repetition Test. In this task participants were initially taught to discriminate between a pair of non-verbal tones pushing one of two computer keys to indicate having heard a high or low tone. They were then trained to make temporal order judgements (TOJ) in response to each of four possible sequences of these high and low tones (high-high, high-low, low-low, low-high), by pushing the response keys in the correct order. When it had been established that the children could accurately perform the TOJ task, they received the four test conditions. Participants completed four blocks of trials in which the tone duration was 75 msec, 125 msec, 175 msec, or 250 msec. Within each block the inter-stimulus interval (ISI) between the tones varied at random from short (8 msec) to long durations (305 msec).

Tallal and Piercy (1973a) demonstrated that for long tone durations (250 msec) the SLI group made temporal-order judgments with the same accuracy as control children. In contrast, the SLI group made more TOJ errors than controls when the tones were of short duration or were separated by brief ISIs. In a second study, Tallal and Piercy (1973b) demonstrated children with SLI made more errors on a task requiring discrimination (same-different) judgments between the same two non-verbal tones in addition to more TOJ errors than control children when tone duration or ISI was brief. As the discrimination task did not require coding of temporal order, the results were interpreted as evidence for an auditory deficit related specifically to the rate at which

auditory information could be processed, rather than to impairments in coding temporal order.

The extension of the rapid auditory processing theory to dyslexic children was made when Tallal (1980) assessed the auditory processing performance of dyslexic and control children (mean age of both groups was 9 years 7 months). Dyslexic children were selected on the basis of having an IQ of > 85 and a reading delay relative to chronological age of at least one year on the Metropolitan Reading Test (Spache, 1963). A nonword reading task was also administered. Participants were trained on a version of the Auditory Repetition Test (Tallal & Piercy, 1973a) in which they were trained to associate two non-verbal tones with computer keys. Participants were then given a TOJ task in which two 75 msec duration tones were separated by a random ISI of between 8 and 428 msec. Results showed there were no significant between group differences for long ISIs. However, when the ISI was decreased (305 to 8 msec) the number of errors made by both groups increased, with the dyslexic group performing significantly less accurately than the control group. A similar impairment at short ISIs was evident on a discrimination task in which participants were required to make same-different judgments on the same two non-verbal tones, which were again separated by random intervals of between 8 and 428 msec. However, the significant between group difference was due to only a sub-group of the dyslexic participants, with only 45% of the dyslexic group making more errors than the worst performing control child. The results of the study provide no evidence for qualitative differences in the reading or cognitive skills of children with and without auditory impairments.

Tallal (1980) also found a moderate between groups correlation between performance on the TOJ task and performance on the Metropolitan Reading Test ($r = .58$). Tallal also reported a significant between groups correlation for the number of errors made in the TOJ task and the number of nonword reading errors ($r = .81$). Tallal

argued that deficits in rapid auditory processing could affect reading because rapid auditory information is crucial for analysing phonetic cues in speech and phoneme awareness is crucial for reading. In particular, Tallal argued that dyslexics would have difficulty for stop consonants such as b and d, for which discrimination requires tracking rapid auditory modulations within a short (50msec) time frame. In contrast, children with rapid processing deficits would be unimpaired for perception of vowel stimuli, such as /a/ and /e/ because the cues for discrimination occur over a longer time frame (200 msec) and the modulations within the speech signal are of a steady state nature.

In a later study, Reed (1989) tested this prediction experimentally and extended Tallal's work by making further links between phonological skill and a rapid auditory processing deficit. Reed tested 20 dyslexic and 20 skilled reading children (age 7-10 years) on tests of TOJ for brief (75 msec) auditory tones, separated by an ISI of between 10 and 400 msec. Reed (1989) replicated Tallal's (1980) original results by demonstrating that the dyslexic group made more TOJ errors than the control group only when the ISI was of short duration. Reed also assessed TOJ performance at varying ISIs for stop-consonant syllables on the /ba/-/da/ continuum and vowel syllables on the /a/ /e/ continuum. According to Tallal's rapid auditory processing theory, the dyslexics would be impaired only for the stop-consonant syllables, as the auditory cues used for discrimination are present only within a short time frame. In contrast, auditory discrimination cues for steady state vowel stimuli are available for longer periods, and discrimination should not be affected by rapid auditory deficits.

In support of this prediction the dyslexic and control groups performed TOJ with equal efficiency for vowel syllables regardless of ISI. However, for the stop-consonant syllables, there was an interaction effect between group and ISI, with the dyslexic group making significantly more TOJ errors than the control group only at short ISIs. Reed

also reported that the dyslexic group made significantly more errors than the control group when required to differentiate between two words beginning with stop-consonants (top \ cop). The dyslexic group also made significantly more errors when discriminating and identifying synthetically manipulated /ba/ /da/ syllables.

On the basis of these results, Reed (1989) concluded that the dyslexic group have a perceptual deficit specific to processing rapid auditory stimuli, thus supporting the rapid auditory processing theory (Tallal, 1980). Reed also proposed that a deficit in rapid auditory processing may interfere with consonant perception, particularly for stop-consonants and may also blur the phonological boundaries between consonants. Reed proposed that this ambiguity may make it difficult to generate adequate phonological representations and may also make the representations themselves less useful.

A problem for Reed's (1989) study is that participants were selected on the basis of scores on a reading measure alone and no measure of intellectual ability was obtained. As discussed in Chapter 1, there is no evidence for unique reading differences between dyslexics with different IQ levels. However, it was also noted that general ability may have a significant impact on performance on psychophysical tasks and that every attempt should therefore be made to match dyslexic and control readers on these measures. Due to the absence of a measure of ability in this case, it could be argued that the impairments observed by Reed (1989) may be due to different ability levels within the two subject groups.

A more recent investigation which did carefully control for general ability and attention deficits also reported rapid auditory processing deficits in dyslexic children (Heiervang, Stevenson & Hugdahl, 2002). Additional evidence for rapid auditory processing deficits has come from studies showing dyslexic groups are impaired at detecting the presence of a brief gap in a sound burst (e.g., Farmer & Klein, 1993). However, the rapid auditory processing theory has faced increasing criticism in recent

years for a number of reasons, not least of which emphasises failures to find rapid auditory processing impairments in dyslexic groups (e.g., Adlard & Hazan, 1998; Breier, Gray, Fletcher, Foorman & Klaas, 2002; Heath, Hogben & Clark, 1999; McAnally & Stein, 1996; Mody, Studdert-Kennedy & Brady, 1997; Nittrouer, 1999; Shulte-Korne, Deimel, Bartling & Remschmidt, 1998). Further, most studies that report significant between group differences also report that impairments only exist in a small sub-group of dyslexics (e.g., Adlard & Hazan, 1998; Manis et al., 1997; Marshall, Snowling & Bailey, 2001; Reed, 1989; Rosen & Manganari, 2001; Tallal, 1980). Other studies have shown problems with recalling tone sequences exist at long ISIs, not just at rapid rates of presentation as predicted by the rapid auditory hypothesis (e.g., Bretherton & Holmes, 2003; Goswami et al., 2002; Nittrouer, 1999; Share et al., 2002; Waber et al., 2001).

An additional criticism of the original studies of Tallal (e.g., Tallal, 1980) and Reed (1989) is that they used control tasks which produced severe ceiling effects for both dyslexic and control reader groups. This raises the question that if the control tasks of less rapid auditory processing had been more sensitive they may also have separated between groups (McArthur & Bishop, 2001). Another line of criticism is that the initial high correlation between nonword reading and rapid processing (Tallal, 1980) has not been replicated in later studies, and rapid auditory processing typically accounts for small or insignificant portions of the variance in phonological skill (e.g., Breier et al., 2002; Heiervang et al., 2002; Share et al., 2002). For example, Heiervang et al. (2002) reported that performance for trials on the Auditory Repetition Test at short durations (75 msec) and short ISIs (8, 15 and 60 msec) was not significantly correlated with nonword reading in either a dyslexic or control group. The original studies also failed to take into account the effect of cognitive ability before examining correlations, an important point given that recent studies have shown general ability accounts for

significant portions of the variance in both phonological and auditory processing performance (Witton et al., 2002).

Finally, a number of studies have proposed that the speech perception impairments reported by the early studies (e.g., Reed, 1989) can be better accounted for within a phonological deficit framework, rather than being due to an underlying auditory perceptual deficit as suggested by Tallal (1980) and Reed (1989). Studies using non-speech stimuli modelled on the frequency changes in real speech have shown that the auditory impairment in dyslexics is specific to phonologically confusable speech stimuli (Adlard & Hazan, 1998; Breier et al., 2002; Bretherton & Holmes, 2003; Griffiths, Hill, Bailey & Snowling, 2003; Materson, Hazan & Wijayatilake, 1995; Nittrouer, 1999). For example, Mody et al. (1997) compared 20 dyslexic and 20 control children (mean age = 8 years) on speech and non-speech stimuli of identical duration and frequency. They found that the dyslexics had difficulty discriminating and judging the temporal order of the syllables /ba/ /da/. However, they were unimpaired for non-speech stimuli synthesised so that they were of identical duration and frequency to the contrast /ba-/da/. On the other hand, the dyslexic group performed in a similar fashion to controls when the /ba/ /da/ syllables were contrasted with more easily discriminable stop CV syllables (/ba-/sa/; /da-/fa/). The original study by Reed (1989), which compared performance on word and syllable discrimination tasks, employed phonetically similar stimuli (e.g., top \ cop and /ba/ /da/). Mody et al. therefore argued the auditory and speech perception impairments observed in the initial studies of Tallal (1980) and Reed (1989) are better accounted for by deficiencies in phonological processing.

2.2 Temporal Auditory Processing

Despite the criticism, the rapid auditory processing theory (Tallal, 1980) has prompted research into other areas of auditory processing in dyslexia. A separate, though related line of research has demonstrated dyslexic groups are impaired relative to control readers in processing temporal auditory stimuli. Temporal aspects of the speech signal are important for carrying the phonological information necessary for speech perception and speech intelligibility (Drullman, Festen & Plomp, 1994; Hirsch, 1959; Shamma, 2003; Shannon, Zeng, Kamath, Wygonski & Ekelid, 1995). For example, slow modulations in the order of 3-4 Hz carry syllabic information along the auditory pathway from cochlea to auditory cortex (Goswami et al., 2002).

A number of researchers (e.g., Goswami et al., 2002; Richardson et al., 2004; Witton et al., 2002) have proposed impairments in temporal auditory processing, particularly for slow rates of frequency and amplitude modulations, may cause subtle speech perception deficits in young dyslexic children, leading to the difficulty with adequately specifying phonological representations in memory. Accordingly, dyslexics have been shown to have higher thresholds for detecting sinusoidal amplitude modulation (SAM) applied to a noise carrier (e.g., McAnally & Stein, 1997; Rocheron, Lorenzi, Fullgrabe & Dumont, 2002). Dyslexic adults have impaired SAM thresholds between 10 and 320 Hz, with the largest difference at 20 Hz (McAnally & Stein, 1997). SAM detection and discrimination thresholds have also been found to be impaired in dyslexic groups relative to controls for amplitude modulated stimuli at 4 and 128 Hz (Rocheron et al., 2002). Electrophysiological data have also shown activation produced by SAM at similar modulation rates is smaller in groups of dyslexic adults (Menell, McAnally & Stein, 1999) and children than controls (Lorenzi, Dumont & Fullgrabe, 2002)

Two recent studies have also provided evidence for impaired temporal envelope perception in dyslexic children (Goswami et al. 2002; Richardson et al., 2004). Both studies used a beat detection task, which required listeners to judge whether an amplitude modulated sound comprised a single element fluctuating in loudness, or two different elements – a distinct beat and a background sound. The sharper the rise time of the modulation, the more likely that the beat will be detected. In both studies, the dyslexic group were impaired relative to controls when rise times were extended. In contrast, they perceived beat easily when rise times were rapid (e.g., 15 msec). The evidence was consistent with a temporal processing deficit in the dyslexic children. Goswami et al., (2002) proposed that the dyslexic group were impaired in their ability to integrate temporal information over relatively long time windows. These temporal deficits could affect phonological representations because of the importance of temporal aspects of the speech signal, such as the slow modulations contained in the temporal envelope, for carrying phonetic information in speech. Consistent with this prediction, Goswami et al. (2002) and Richardson et al. (2004) demonstrated beat detection performance could account up to 25% of the variance in reading and spelling ability and up to 22% of the variance in phonological processing, even after accounting for the effects of non-verbal IQ, vocabulary and age.

A number of recent studies have also found auditory temporal processing deficits in groups of dyslexic adults and children using different rates of amplitude and frequency modulation of carrier tones (e.g., Edwards et al., 2004; Ramus et al., 2003; Talcott et al., 1999; Talcott et al., 2003; Witton et al., 1998; Witton et al., 2002). For example, in a recent study Witton et al. (2002) assessed groups of 17 dyslexic and 17 control adults on their sensitivity to 2 and 240Hz FM and 2 and 20Hz AM. The study chose to focus on sensitivity to amplitude and frequency modulations because they are

ubiquitous in the speech signal and they can appear acoustically at various grain-sizes of phonological information (Witton et al., 2002).

The selected modulations differed in the type of auditory processing required. Detection of sinusoidal FM below about 40 Hz is performed by tracking the actual modulation of the carrier tone in time (Hartman, 1997; Talcott et al., 1999). In contrast, detection of more rapid FM (e.g., 240 Hz) is performed by an auditory mechanism tuned to the pitch of the modulation frequency (Talcott et al., 1999). The perception of slow and rapid FM is therefore performed by different auditory mechanisms. At slower rates, perception relies on temporal cues, while at more rapid rates; perception relies on spectral cues. Within the literature, rates of AM such as the 2 and 20 Hz stimuli, are presumed to be slow enough to be tracked in time. The detection mechanisms are therefore thought to be temporal in nature (e.g., Menell, McAnally & Stein, 1999; McAnally & Stein, 1997; Talcott et al., 1999). There is some evidence to suggest that sinusoidal AM is detected using pitch (non-temporal) cues at threshold (Demany & Semal, 1986). Nevertheless, the dominant interpretation of these tasks within the literature is that they reflect a form of temporal processing. The selected tasks therefore allowed the authors to investigate if there was dissociation between detection performance for slow and rapid modulation rates, or whether the impairment extended to all auditory stimuli.

The tasks required participants to choose the modulated tone from a stimulus pair consisting of a modulated and a pure tone stimulus, each of 1000 msec duration separated by a silent 500 msec interval. Significant between group differences were found for 2 Hz FM (Cohen's $d = 1.31$) and 20 Hz AM (Cohen's $d = .65$), with the dyslexic group having significantly higher thresholds than the control group, indicating that they were less sensitive to these types of auditory stimuli. In addition to statistical significance the strength of the effect sizes demonstrate the reliability and practical

significance of the results. In contrast, no significant between group differences were evident for 240 Hz FM ($d = .59$) and 2 Hz AM ($d = .31$) stimuli. As the thresholds of the dyslexic group for the 2 Hz AM stimuli were similar to the control group, these data demonstrated that the dyslexic group were not impaired at detecting all modulations slow enough to be tracked in time. In addition, support for the notion that the dyslexic group were unimpaired for acoustic stimuli that are not temporal in nature was presented.

The Witton et al. (2002) modulation detection task, particularly the 2 Hz FM stimulus, has become the most frequently used task for measurement of auditory sensitivity in dyslexics (e.g., Ramus et al., 2003; Witton et al., 1998; Huslander et al., 2004; Talcott et al., 1999; Talcott, Witton et al., 2000; Talcott et al., 2003). For example, findings of dyslexic impairment for processing temporal frequency modulations at 2 Hz have been replicated in Norwegian children (Talcott et al., 2003) and in dyslexic adults by (Ramus et al., 2003). Using a slightly different task, sensitivity for detection of FM around 20 Hz has also been shown to be impaired in dyslexic children (Edwards et al., 2004). Importantly, sensitivity to temporal rates of AM and FM has also been shown to be significantly related to phonological and literacy skills (e.g., Witton et al., 2002; Witton et al., 1998). For example, Witton et al. (2002) demonstrated thresholds for 2Hz FM could account for 34% and thresholds for 2 Hz AM 9% of the variance in nonword reading (a sensitive measure of phonological skill in adults; Rack, Snowling & Olson, 1992), after accounting for non-verbal ability. The 240 Hz FM variable did not account for additional variance in nonword reading after accounting for IQ. Witton et al. (1998) have also reported that sensitivity to temporal, but not spectral rates of FM are moderately correlated with nonword reading ability. Witton et al. showed that sensitivity to 2 Hz FM ($r = .526$) and 40 Hz FM ($r = .467$) was significantly correlated with nonword reading accuracy in 21 dyslexic and 23

normal reading adults. In contrast, sensitivity to 240 Hz FM was not correlated with nonword reading ($r = -.03$).

Similar relationships between temporal auditory processing and phonological skill (nonword reading and spoonerisms) have been reported in studies using a normative design. For example, in a small ($n = 32$) unselected sample of children, Talcott et al., (1999) found significant correlations existed between thresholds for 2 Hz FM and nonword reading ($r = -.74$), performance on a spoonerism task ($r = -.68$) and word reading skill ($r = -.7$). Sensitivity to 240 Hz FM was not significantly related to any reading or language variable. Talcott et al. (1999) also reported sensitivity to 2 Hz FM correlated significantly with performance on a test of exception word naming ($r = -.59$), which was used to assess orthographic coding skill. Note however, that many exception words can be at least partly decoded on the basis of regular sound-letter rules (e.g., answer; Vellutino et al., 1994). Thus, successful performance on an exception word reading task may be aided by phonological processing. Exception word reading performance may also be affected by reading ability and exposure to text (Vellutino et al., 1994). It is therefore unclear how the observed relationship between thresholds for 2 Hz FM and exception word reading should be interpreted.

In a later study, which employed a different measure of orthographic coding ability, no relationship was found between orthographic coding and acoustic processing thresholds (Talcott, Witton et al., 2000). Talcott, Witton et al. reported that sensitivity to 2 Hz FM, but not 240 Hz FM accounted for a significant unique portion of the variance in phonological skill (defined as the first principal component of performance on nonword reading and spoonerism tasks) after removing the effects of both reading skill and general ability. In contrast, no significant relationship was found between orthographic skill (defined by taking the first principal component of performance on an exception word reading and a pseudohomophone task) and either auditory variable, after

accounting for reading ability and general ability. However, the specificity of the relationship between acoustic processing and phonological skill has not been supported by all research studies. For example, in a follow-up study with a much larger unselected sample of children ($n = 350$), Talcott et al. (2002) found auditory frequency discrimination ability could account for 4% of the variance in a combined reading and spelling measure, 4% of the variance in phonological skill (nonwords and spoonerisms) and 6% of the variance in a combined measure of exception word reading and pseudo-homophone discrimination after accounting for cognitive ability, but not reading ability.

Thus, there is evidence to show that dyslexic groups are impaired when required to process basic auditory temporal information, such as amplitude and frequency modulations, which are slow enough to be tracked in time by the auditory system. A number of studies have also demonstrated thresholds for temporal auditory stimuli are significantly related to performance on phonological and orthographic processing measures and also to overall reading skill (e.g., Witton et al., 1998; Witton et al., 2002; Talcott et al., 1999; Talcott, Witton, McLean et al., 2000). On the basis of these correlations, and because of the importance of modulations within the speech waveform for carrying phonetic information, it has been argued that an auditory temporal deficit in dyslexia may affect development of phonological representations (e.g., Goswami et al., 2002; Richardson et al., 2004; Witton et al., 2002). However, like the rapid auditory theory (Tallal, 1980) before it the temporal processing theory has been criticised for a number of reasons.

Detection of FM at 2 Hz has been a strong discriminating variable between dyslexic and control groups in a number of studies (e.g., Ramus et al., 2003; Witton et al., 2002). However, at least one study has failed to find dyslexic impairments on a similar task (Hill et al., 1999). Hill et al. tested auditory processing in groups of 12 dyslexic and 12 control adults matched for age and IQ, using a frequency modulation

detection paradigm. The dyslexics were selected on the basis of a documented history of reading and spelling problems and current phonological difficulties. These selection criteria were used because adult dyslexics often compensate for their reading difficulties, so discrepancy criteria are inappropriate (Hill et al., 1999) and phonological impairments are thought to be at the core of dyslexia (Stanovich, 1986). Two carrier tones (1 and 6 kHz) were used with the rate of modulation set at 2.5 Hz. At 1 kHz the stimulus was comparable to the 1 kHz tone modulating at 2 Hz used by previous studies (e.g., Witton et al., 1998; Witton et al., 2002). The 6 kHz stimulus was used as a control task because at this frequency rate, the stimulus modulates too rapidly to be tracked in time by temporal mechanisms. The difference in thresholds between the two groups was not significant for either frequency rate. The authors therefore argued that the data could not be interpreted in terms of a specific auditory temporal processing deficit. However, it should be noted that this conclusion was based solely on a measure of statistical significance (p values) and no measures of effect size were reported. It is therefore difficult to directly compare this study with others in the literature.

Criticism can also be levelled at studies of temporal auditory processing for an over-reliance on p values as measures of significance, rather than examining effect sizes and individual data in addition to group means. As has been noted earlier in this review, at least one study (Witton et al., 2002) reported a moderate effect size for the non-temporal 240 Hz FM stimulus, which was discounted on the basis of a non-significant p value. The data from an additional study also suggests dyslexic impairments in processing frequency and amplitude modulations may not be confined to temporal stimuli. Hari, Saaskilahti, Helenius and Uutela (1999) compared groups of 20 control and 13 dyslexic adult readers on their ability to perform pitch discrimination for pairs of pure tones at ~1 kHz (producing spectral pitch) and for ~80 Hz AM of white noise bursts (producing only periodicity pitch analysed on the basis of temporal

information). The dyslexic group had higher discrimination thresholds for both tasks, indicating that at least in this sample of dyslexics the auditory impairment was more general in nature. No effect size data was available from the study.

When individual data points are investigated it is also generally found that auditory deficits exist in dyslexia, but only in a small sub-group (Edwards et al., 2004; Lorenzi et al., 2000; Ramus et al., 2003; Richardson et al., 2004; Witton et al., 1998; Witton et al., 2002; see also Ramus, 2003 and Rosen, 2003 for reviews). For example, Edwards et al., (2004) defined abnormal (deviant) auditory processing performance as a threshold greater than 1 SD above the mean threshold of the control group on a frequency detection task (2 Hz FM). Using these criteria they found 33% of the dyslexic group had abnormal auditory temporal processing scores. They also found ~8% of the control participants had auditory impairments using the same criteria. In the data displayed by Witton et al. (1998) it can also be seen that only 7 of 18 dyslexic participants had thresholds for detection of 2 Hz FM greater than the highest threshold in the control group.

2.3 Summary

On balance, it appears as if auditory processing deficits exist in dyslexic groups; although impairments may be confined to a small sub-group rather than being a universal characteristic of dyslexia. Arguably, the most important recent study has been that of Witton et al. (2002) who demonstrated that a group of dyslexic adults were specifically impaired at detecting frequency and amplitude modulations that were slow enough to be tracked in time. This study aimed to add to the literature by providing an independent external replication of Witton et al.'s study in addition to replicating the effects within the same participant groups at separate points in time. On the basis of previous research it was expected that the dyslexic group would have a deficit for the

temporal stimuli 2 Hz FM and 20 Hz AM, but not for 2 Hz AM. It was also expected that the dyslexic group would also be unimpaired for the non-temporal control stimulus 240 Hz FM. There is also some inconsistency within the literature with regard to the relationships that have been found between auditory processing and reading skills. Due to this inconsistency, the current study will examine the relationship between auditory processing and reading skills in an external replication of the existing research (e.g., Talcott, Witton et al., 2000; Witton et al., 2002). It was expected that significant relationships would be observed between the temporal stimuli, such as 2 Hz FM, and reading skills, but not between the control stimulus 240 Hz FM and reading skills.

In addition to deficits in processing dynamic temporal information in the auditory system, dyslexia has been associated with impairments in processing temporal information within the visual domain, particularly in the magnocellular visual system. The following chapter will review the evidence for visual deficits in dyslexics and discuss the possible link between visual impairments and reading difficulties.

3.0 Visual processing in dyslexia

3.1 Introduction

The magnocellular deficit theory reflects the view, made popular by Orton (1925), that dyslexia can be a result of visual impairment, which in turn can affect the perception of letters and words. While Orton's view has been shown to be incorrect (Vellutino, 1979), the obvious involvement of the visual system in reading has led many to propose visual deficits as a possible source of reading difficulties, at least in some dyslexics (e.g., Lovegrove, 1993; Stein & Walsh, 1997). Before reviewing the evidence for magnocellular deficits in dyslexia, the properties of the visual system will be summarised.

3.2 Structure and Function of the Visual Pathways

The retinocortical visual system consists of two major visual pathways, which conduct 90% of the information from the retina to the occipital lobe of the cortex (V1; Livingstone & Hubel, 1987). These pathways are now commonly referred to as the magnocellular (M) and parvocellular (P) pathways. The functional properties of the M and P systems are presented in Table 1.

The M system was initially thought responsible for detection of low spatial frequencies below 0.2 - 3.5 c/deg (e.g., Legge, 1978; Tolhurst, 1975) and at both low and high spatial frequencies when stimuli were of high temporal frequency or of short duration (Blakemore & Vital-Durand, 1986). However, later studies primarily in the monkey visual system have demonstrated lesions to M layers of the lateral geniculate nucleus (LGN) have very little effect on sensitivity to the spatial or temporal properties of the stimulus when either spatial or temporal frequency is manipulated independently

(Merigan & Maunsell, 1993). However, lesions to the M pathway severely reduce contrast sensitivity for stimuli at both high temporal (e.g., 10 Hz) and low spatial frequencies (e.g., 1 c/deg). In contrast, lesions to the P layers of LGN in monkeys leads to significant reductions in contrast sensitivity across a range of spatial frequencies, down to as low as 0.5 c/deg (Merigan, 1989; Merigan & Eskin, 1986; Merigan, Katz & Maunsell, 1991; Schiller, Logothetis & Charles, 1990 a,b). The only stimuli that appear unaffected by P lesions to monkey LGN are those with both low spatial and high temporal frequencies (Merigan & Eskin, 1986). Thus, maximum separation of function between the M and P pathways occurs only when the stimuli are of low spatial and high temporal frequency.

The M and P pathways also differ in their response to colour. P pathway cells respond to colour change, regardless of the relative luminance of the colours (Derrington & Lennie, 1984). In contrast, M pathway cells are thought to be achromatic because they show virtually no response to colour alteration when the luminance of the colour is balanced (isoluminance; Merigan & Maunsell, 1993). However, M cells do show a non-selective response to colour transitions at isoluminance (Lee, Martin & Valberg, 1989; Schiller & Colby, 1983). M and P cells also differ in the time course of their response to visual stimuli (Merigan & Maunsell, 1993). M cells respond in a more rapid and transient manner (Kaplan, Lee & Shapley, 1991; Zeki, 1993; Zeki & Shipp, 1988) and they also conduct impulses more rapidly than P cells (Kaplan & Shapley, 1982).

Functional properties of the M and P pathways (adapted from Lovegrove, 1993).

M pathway	P pathway
Highly sensitive to contrast	Less sensitive to contrast
Sensitive to stimuli of low spatial and high temporal frequency	Sensitive to stimuli of low temporal frequency and across a range of spatial frequencies
Responds in a rapid, transient manner	Responds more slowly throughout the lifetime of the stimulus
Achromatic	Colour sensitive

Anatomically, the M and P pathways begin in the retina, where the ganglion layer contains large (M) cells and smaller (P) cells. Beyond the retina, the impulses produced by the M and P cells project via the optic nerve, optic chiasm and optic tract to LGN (Zeki, 1993). Each LGN is sub-divided into M and P layers. The upper four layers receive input from P cells in the retina. The lower two layers receive the projection of the M ganglion cells. The efferent projections from the M and P layers of LGN continue via the optic radiation to a part of the cortex situated in the occipital lobe (Merigan & Maunsell, 1993; Simos, 2002; Zeki, 1993). This area has different names, such as primary visual cortex, area 17, calcarine cortex, and V1, but for this review it will be referred to as V1.

V1 consists of six main layers that show distinct cellular composition and patterns of connectivity (Simos, 2002). Within V1, the separation of M and P pathway afferents is maintained, with layers 4C β and 4A receiving the majority of afferents from P layers of LGN and 4Ca receiving M input (Simos, 2002). V1 contains all the sub-modalities of vision i.e., motion, wavelength (colour), orientation and depth. V1 is thought to contain a detailed topographic map of the visual field seen at the retina. It acts as a distributor of information by segregating visual signals and sending them on to

specialised visual areas in the surrounding extra striate cortex for further processing (Zeki, 1993). Within the extra striate visual system beyond V1, the accumulated evidence also supports the existence of functionally distinct pathways similar to that observed in the M and P pathways up to V1 (Simos, 2002). Indeed, some authors have proposed that a direct correspondence exists between the low level M and P pathways and a dorsal visual pathway projecting to the parietal cortex and a ventral pathway that projects to the inferior temporal cortex (e.g., Kandel, 1991; Livingstone & Hubel, 1987; Ungerleider & Mishkin, 1982). However, this proposal may be an oversimplification, as there is substantial intermixing of M and P inputs to extra striate areas (Zeki, 1993). Nevertheless, research on the extra striate cortex has demonstrated that certain cortical areas process information about specific visual qualities (Goldstein, 2002). Figure 1 presents the structure and connections within the retinocortical and extra striate visual systems. The review of the visual system will continue below with particular emphasis placed upon research that has demonstrated functional specialisation for areas within the dorsal and ventral streams.

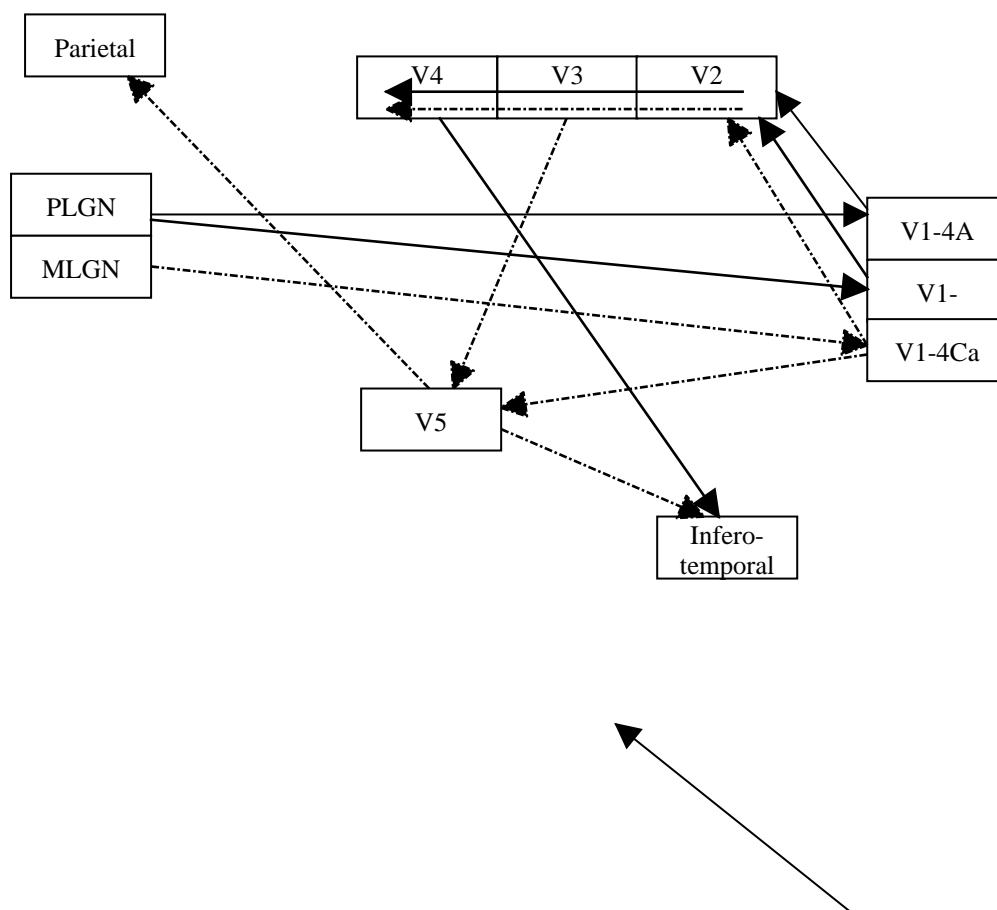


Figure 1. The visual system. Straight lines represent P input and dotted lines represent M input. Adapted from Johnson (1997).

3.2.1 *The ventral stream*

The ventral stream projects to infero-temporal areas and is thought to be involved with detailed object discrimination and object identification (Maunsell & Newsome, 1987; Ungerleider & Mishkin, 1982). It receives both M pathway afferents via V5 and V4 and P pathway afferents via V4. Within the ventral stream, visual area V4 has received the most attention. Cells within V4 are arranged in columns, each of which contains neurons that respond to similar shapes (Goldstein, 2002). These neurons receive both M and P pathway input directly through V1 and indirectly through V2 (Zeki, 1993). Neurons within V4 are responsible for perception of fine visual details (form, pattern and texture perception) and colour perception (Simons, 2002; Zeki, 1973), but not motion (Schiller, 1996). Thus, V4 is specifically concerned with colour and form processing. Visual area V3 in the ventral stream may also be involved in processing of dynamic form (Zeki, 1993).

3.2.2 *The dorsal stream*

The dorsal stream projects to posterior parietal regions and has been described as being involved in visuospatial analysis (Ungerleider & Mishkin, 1982). Research in

primates and patients with parietal lesions has also demonstrated that the parietal cortex is important for detection of visual motion (e.g., Zihl, Cramon & Mai, 1983). The parietal lobe also contains the mechanisms of visual attention (Husain, 1991). These properties make the parietal lobe important for visual tasks such as localising objects in space and guiding eye movements towards visual targets (Dursteler & Wurtz, 1988; Maunsell & Newsome, 1987; Ungerleider & Mishkin, 1982). In addition to higher-level processes such as localising objects and attentional processes, areas in the dorsal stream are important for perceptual functions, such as detection of motion.

3.2.2.1 Motion perception

Although M cells in retino-cortical visual areas are sensitive to the presence of motion in a stimulus, the information they provide is generally ambiguous about motion direction. Global perception of movement is based on activity of neurons in “higher” visual areas (Goldstein, 2002). One area in the dorsal stream, visual area V5 (also known as MT), which has homologues in humans and monkeys (Braddick, Atkinson, Wattam-Bell, 2003), has been particularly studied for its role in motion perception. V5 is located at the temporal-parietal junction within the superior temporal sulcus and contains a high density of motion sensitive neurons (Dubner & Zeki, 1971; Maunsell & Newsome, 1987; Maunsell & Van Essen, 1983; Watson et al., 1993; Zeki, 1974). Within V5, neurons that prefer specific directions are arranged in columns (Albright, Desimone & Gross, 1984) and each column codes for a particular direction of motion in a restricted region of the visual field (Maunsell & Van Essen, 1987). Within these columns the responses of individual cells are summed through a process referred to as probability summation to provide information regarding the global motion of the stimulus. Anteriorly and inferiorly several other visual areas border V5, including MST (Zeki, 1980). These areas receive direct input from V5 and are specialised for processing

different types of motion (Zeki, 1993). It is therefore common to refer to the V5 complex.

The role of the V5 complex in motion perception is supported by early single cell electrode studies, which showed V5 neurons fire in response to motion stimuli within their visual field (Zeki, 1974). Evidence also comes from studies utilising more sophisticated imaging technologies which have demonstrated that when viewing motion stimuli the area of greatest activation outside of V1 lies within V5 (Zeki, 1993). The role of the V5 complex in motion perception is also supported by data from lesion studies. Lesions to areas within the V5 complex in monkeys produce severe, though transient, deficits in motion sensitivity (Newsome & Pare, 1988). Larger lesions within the V5 complex cause more permanent deficits in motion perception (Merigan, Byrne & Maunsell, 1991; Newsome & Pare, 1988; Newsome, Wurtz & Dursteler, 1985; Schiller et al., 1990; Yamasaki & Wurtz, 1991) and complete, bilateral lesions within V5 complex cause permanent deficits in speed discrimination thresholds, direction thresholds and detection of global motion (Pasternak et al., 1991). In contrast, lesions to primate area V5 do not cause any difficulties in the processing of colour (Schiller, 1993). Lesions to V5 in humans also lead to motion discrimination problems (Baker, Hess & Zihl, 1991; Zihl et al., 1983).

The retino-cortical inputs to V5 are almost exclusively from the M pathway. Research has demonstrated that inhibiting M cells at LGN in primate brains leads to complete suppression of activity in V5 in response to moving and flashing stimuli (Maunsell et al., 1990). It has also been demonstrated that motion sensitivity is reduced in primates following lesions to the M pathway at LGN (Merigan, Byrne et al., 1991), while inhibition of the P pathway following injections to P layers of LGN in primate brains has little effect on V5 response (Maunsell et al., 1990). Thus, V5 is specialised for motion processing and can be referred to as part of a predominately M pathway that

projects to both the inferior temporal cortex and parietal cortex, with the dominant input being to parietal areas (Zeki, 1993).

3.3 Processing in the Retinocortical M and P Pathways in Dyslexics

A large number of investigations, beginning with the work of Lovegrove and his collaborators (e.g., Lovegrove et al., 1980; Slaghuis & Lovegrove, 1984, see Lovegrove, 1993 for a review), have taken advantage of the dissociation in function of the M and P pathways up to V1 to study the integrity of these two pathways in dyslexics. The evidence for M deficits in dyslexics comes from anatomical, electrophysiological and behavioural data, all of which will be reviewed in the following sections.

3.3.1 Anatomical data

Anatomical evidence is limited to a single histological study. Galaburda and Livingstone (1993) examined the brains of 5 dyslexics and 5 controls post mortem. Inspection by three observers found no abnormalities within the P layers of LGN in either group. In contrast, the M layers of LGN in the dyslexic brains were more disorganised and the cell bodies were smaller and more variable in shape and size. Compared to control brains, M cells were on average 27% smaller than in control brains. These data have been interpreted as powerful evidence of the existence of M deficits at LGN in dyslexics.

3.3.2 *Behavioural data*

3.3.2.1 *Visual evoked potentials*

Physiological studies have used visual cortical evoked potentials (VEP) in response to visual stimuli to investigate M and P processing in the retino-cortical visual system up to the level of V1. Livingstone, Rosen, Drislane and Galaburda (1991) presented groups of dyslexic and control adult readers with checkerboard patterns flickering at low and high contrast. The pattern of results for the dyslexic group was consistent with the hypothesis of a selective M pathway deficit. That is, for low contrast (2% and 4%) stimuli flickering at 15 Hz (to which the M system is responsive) the dyslexic group showed reduced VEP amplitudes. However, their response to static stimuli or to high contrast (30%) stimuli (to which the P system is responsive) was similar to controls.

Several other studies have also found reduced VEP responses for dyslexic groups when stimuli are presented under conditions in which the M pathway is thought to dominate visual processing (e.g., Kubova, Kuba, Peregrin & Novakova, 1996; Lehmkuhle, Garzia, Turner, Hash & Baro, 1993; May, Lovegrove, Martin & Nelson, 1991). However, at least three studies have failed to find between group differences in VEPs for stimuli processed by the M pathway in the retino-cortical visual system (Farrag, Kheder & Abel-Naser, 2002; Johannes, Kussmaul, Munte, Mangun & George, 1996; Victor, Conte, Burton & Nass, 1993) and at least one study has argued that a group of dyslexic children had visual impairments consistent with impairment within the P system (Farrag et al., 2002).

Farrag et al. (2002) measured VEP in response to black and white checkerboard patterns presented at high and low luminance contrast, high and low spatial frequency and at two temporal frequencies (1 and 8 Hz) in 52 dyslexic and 41 skilled readers. The

dyslexic group were selected on the basis of a Full-Scale IQ of > 90 and a reading age of at least 1.5 years below chronological age on a test of single word reading. Results demonstrated the dyslexic children had a significant delay in VEP for a high contrast, low temporal frequency (1 Hz) checkerboard stimulus compared to control readers. There were no other recorded differences between the VEP in either group. Farrag et al. therefore proposed the P pathway, rather than the M pathway is impaired in dyslexics.

3.3.2.2 Visible persistence

Visible persistence refers to the continued perception of a stimulus after offset. Persistence is assumed to reflect ongoing neural activity initiated by stimulus presentation (Lovegrove, 1993). In normal adults, the duration of visible persistence increases with increasing spatial frequency (Bowling, Lovegrove & Mapperson, 1979). This effect has been explained in terms of M –on – P inhibition: as spatial frequency increases, the inhibition decreases, allowing the P system to operate for longer (Breitmeyer, Levi & Harwerth, 1981; Slaghuis & Lovegrove, 1984). In a typical persistence task, participants view trials consisting of a low luminance grating-blank-grating stimulus. The duration of the blank inter-stimulus interval (ISI) is the dependent variable. Participants are instructed to report the presence of a clear blank interval between gratings. Slaghuis and Lovegrove (1984) tested a dyslexic group with a severe reading delay (~ 4 years) and a control group. The dyslexic group showed less visible persistence as a function of spatial frequency than controls, reflecting poorer M system function (Slaghuis & Lovegrove, 1984). This effect has been replicated a number of times in children (e.g., Badcock & Lovegrove, 1981; Lovegrove, Heddle & Slaghuis, 1980; Slaghuis & Lovegrove, 1985). In contrast, when visible persistence is measured under conditions in which M pathway function is reduced (using a uniform flickering field mask) visible persistence differences between the groups are not apparent

(Slaghuis & Lovegrove, 1984). These data have been interpreted as evidence for a specific M pathway deficit.

However, Georgeson (1985) has criticised this conclusion on the basis of the argument that measures of visible persistence are unreliable in adults, and therefore, probably even less reliable in children with learning difficulties. Lovegrove and Slaghuis (1989) investigated this claim by assessing performance on visible persistence measures in groups of dyslexic ($n = 35$) and skilled reading ($n = 35$) children at three points in time. The time between testing sessions varied for each child (between one week and three months). Results demonstrated that the dyslexic group performed more poorly than the control group at all three times. However, the large difference in mean cognitive ability scores in the dyslexic ($M = 96.2$) and control ($M = 110$) groups complicated interpretation of the significant group differences in terms of a simple M pathway deficit. More importantly, only moderate correlations (Pearson's $r = .45-.57$) were observed between performances across the three measures, providing evidence of instability in the children's response pattern across time.

3.3.2.3 Spatial and temporal frequency processing

Dyslexic and control groups have also been compared on tasks which measure the minimum contrast required to correctly detect the presence of a sinusoidal waveform at different spatial frequencies. Contrast sensitivity plotted as a function of spatial frequency is referred to as the contrast sensitivity function (CSF; Lovegrove, 1993). The typical finding in these studies is that dyslexics are less sensitive than controls at low spatial frequencies (Hill & Lovegrove, 1993; Lovegrove et al., 1980; Lovegrove, Martin, Bowling, Blackwood, Badcock & Paxton, 1982; Martin & Lovegrove, 1984). For example, in one of the earliest studies Lovegrove et al. (1980) tested groups of 14 year old boys ($n = 10$) matched for age and socio-economic status. The dyslexic boys were severely impaired readers, with an average reading delay of 5 years. CSF for low

luminance gratings of 2, 4, 12 and 16 c/deg were measured. The dyslexic group were significantly less sensitive than controls for the 2 and 4 c/deg stimuli, but did not differ in contrast sensitivity at higher (12 and 16 c/deg) spatial frequencies.

It should be noted that these early studies were not specifically designed to detect the presence of a magnocellular deficit. Rather they were designed to evaluate visual processing in general in dyslexics (Lovegrove, personal communication). However, the results have since been interpreted as providing evidence in favour of an M pathway deficit (e.g., Borsting et al., 1996; Stein & Walsh, 1997). Given that the M pathway mediates detection only when stimuli are of both low spatial and high temporal frequencies (Merigan & Maunsell, 1993) it is difficult to reconcile these CSF studies as evidence for a specific M system deficit in dyslexics.

Dyslexics and controls groups have therefore been compared on tasks that more directly measure M pathway function (e.g., Felmingham & Jacobson, 1995; Martin & Lovegrove, 1987; Slaghuis & Ryan, 1999). In these tasks, participants view a sine wave grating counter phasing (moving one cycle from right to left and back) at varying speeds. Participants are required to detect the presence of flicker (Lovegrove, 1993). A number of these studies have presented data consistent with the hypothesis for a specific deficit within the M pathway. For example, Martin and Lovegrove (1987) demonstrated a dyslexic group were significantly less sensitive to flicker than controls when the stimuli were of low spatial (2 c/deg) and high temporal frequency (5-25 Hz). They also demonstrated that the impairment became more marked as temporal frequency increased, as would be predicted by an M deficit. These data have been replicated by Felmingham and Jacobson (1995), who tested the contrast sensitivity of groups of dyslexic ($n = 10$) and control ($n = 10$) children for low spatial frequency (2 c/deg) stimuli flickering at between 5 and 25 Hz. Consistent with an M deficit, the dyslexic group were significantly less sensitive to flicker at higher temporal frequencies

(15, 20 and 25 Hz) and the size of the deficit increased with temporal frequency. Slaghuis and Ryan (1999) have also demonstrated that relative to a control group, a group of dyslexic children were impaired for low spatial (0.5, 2 c/deg) and high temporal frequency gratings (e.g., 8 and 18 Hz), which maximally stimulate the M pathway.

Evidence for contrast sensitivity impairments in children and adults showing specific profiles of dyslexia has also been reported. As mentioned in Chapter 2, there is considerable discussion within the literature regarding the existence of dyslexic subtypes. The consensus is that individuals showing a phonological profile are typical of a developmental disorder (dyslexia). In contrast, individuals showing a surface profile are typical of a developmental delay in acquiring reading skills. Therefore, findings that only participants showing a phonological or mixed phonological/surface profile have M pathway impairments is still consistent with the theory of an M pathway deficit in dyslexia. For example, Slaghuis and Ryan (1999) demonstrated that only children with phonological or mixed dyslexic profiles had reduced sensitivity to flicker for low spatial (0.5, 2 c/deg) frequency gratings flickering at 4, 8 and 16 Hz. Borsting et al. (1996) have also reported findings of M-deficits in phonological/mixed profile dyslexic adults. They tested groups of adult control readers and two groups of poor adult readers on a flicker sensitivity task. One group showed a surface profile, while the other had more severe reading deficits characterised by both phonological and surface deficits (mixed profile). There was no significant reader group by stimulus type interaction, but there was a main effect of reader group. Contrast analyses showed the mixed group, but not the surface group were less sensitive to flicker than control for low spatial frequency (0.5, 1 and 2 c/deg) stimuli, drifting at 10 Hz. Neither dyslexic group was impaired for higher spatial frequency stimuli. These data are typically interpreted as evidence for an M deficit in the more severely reading disabled mixed group.

However, this interpretation has been criticised on statistical grounds. For example, Stuart et al. (2001) point out that the interaction test is the appropriate test for testing an M-specific deficit. The significant main effect observed by Borsting et al. provides evidence for general difficulties with the tasks, but no evidence for an M-specific deficit. As Stuart et al. argue, there is no justification for conducting specific comparisons post hoc in the absence of a significant interaction. The evidence for M-specific deficits in dyslexic subgroups is therefore inconsistent.

Although seemingly supportive of a specific M pathway deficit in dyslexic groups, a number of other investigations, which have employed tasks designed to maximally stimulate the M pathway, have not found evidence of M pathway impairments (Hayduk, Bruck & Cavanagh, 1996; Walther-Muller, 1995; Williams et al., 2003). For example, Walther-Muller (1995) used 1 and 12 c/deg gratings flickering at 16.8 Hz to assess M pathway function in groups of dyslexic and control children. The parameters of the 1 c/deg stimulus at 16.8 Hz stimulus maximally stimulate the M pathway, while the 12 c/deg stimulus preferentially stimulated the P pathway. No significant between group differences were observed for either stimuli. The dyslexic children were of average IQ and scored below the 5th percentile on an oral reading test (German). These children therefore had quite severe reading difficulties, although it is unclear whether the reading lag they experienced is comparable to the 5-year lag observed in the studies by Lovegrove and colleagues.

Hayduk et al. (1996) tested groups of dyslexic and control adults ($n = 20$) with 2 and 12 c/deg gratings that were either static or flickering at 33Hz, while Williams et al. (2003) tested groups of dyslexic children with a very low spatial frequency Gaussian blob flickering at 8.33 Hz and an 8 c/deg static grating. Both studies reported that no significant between group differences existed for stimuli mediated by either the M or P pathway. A number of other studies have also failed to find significant between group

differences on similar sensitivity tasks (e.g., Cornelissen et al., 1995; Spinelli et al., 1997). However, interpretation of these results is complicated by the differences in participant criteria and task parameters.

A recent study has argued that task procedure may also be important. Ben-Yehudah, Sackett, Malchi-Ginzberg and Ahissar (2001) compared two task procedures. In a temporal two-alternative forced-choice paradigm, stimuli with spatial frequency between 0.5 and 12 c/deg and temporal frequency of 1 or 10 Hz, were presented in sequential fashion. Ben-Yehudah et al. (2001) reported a group of dyslexic adults ($n = 38$) were less sensitive to contrast than a control group ($n = 42$) for all spatial frequencies at 10 Hz, but were unimpaired at for the 1 Hz stimulus. The results were interpreted in favour of a specific M deficit. In a second experiment, contrast sensitivity was determined for 0.5 c/deg gratings flickering at 5-25 Hz and static gratings of 1,2,4,8 and 16 c/deg. Instead of a temporal forced choice paradigm, only one interval was used and the task required participants to decide if the grating appeared in the upper or lower part of the screen (spatial two-alternative forced-choice paradigm). No significant between group differences emerged. Ben-Yehudah et al. (2001) therefore proposed that the type of perceptual comparison required by the task impacts on the performance of dyslexics more than the stimulus characteristics. The requirement to retain an accurate trace of a stimulus for subsequent comparison appears to be difficult for dyslexics. However, the argument for a deficit in perceptual memory is weakened by the failure to find group differences for the 1 Hz stimuli. Further weakening this explanation is that at least two studies have failed to find significant between group effects with a temporal forced-choice paradigm (Walther-Muller, 1995; Williams et al., 2003).

Inconsistencies in the literature may also result from differences in the criteria used to select reader groups. Of the studies that reported null results, three (Cornelissen et al., 1995; Hayduk et al., 1996; Spinelli et al., 1997) have used participants with far

less severe reading impairments than the participants used in previous studies (e.g., Lovegrove et al., 1980; Slaghuis & Lovegrove, 1984). Indeed, Hayduk et al. used adults who only scored below the 30th percentile on a test of word identification, when it is generally accepted that a score of less than the 15th percentile represents a reading impairment (Snowling, 2000). Spinelli et al. (1997) also tested children showing a surface profile, a condition believed to reflect a delay in reading development rather than dyslexia (Manis et al., 1996; Stanovich et al., 1997). Failure to employ task conditions that maximise M processing may also account for some of the inconsistencies in the literature. For example, Cornelissen et al. (1995) measured sensitivity to contrast using high luminance (105 cd/m²) stimuli, which preferentially stimulate the P pathway.

3.4 Summary of Retinocortical Processing in Dyslexics

In summary, the large amount of inconsistent evidence makes it difficult to conclude that all dyslexics have low-level visual deficits. It is also difficult to reconcile a large proportion of the results with the theory of a specific M pathway deficit. However, the anatomical data (Galaburda & Livingstone, 1993), which demonstrated abnormalities within M, but not P layers of LGN in dyslexic brains, makes it difficult to argue M pathway deficits do not exist at all in dyslexics. Interpretation of the literature is complicated by the lack of a universally accepted definition of dyslexia and the difficulty developing stimuli that completely isolate one or other of the M or P processing systems. Consequently, more recent research has focused on higher levels of the visual system in which processing of various stimuli can be more easily isolated. Visual area V5 has received the most attention as it is specialised for processing of motion (Baker et al., 1991; Merigan et al., 1991; Newsome & Pare, 1988; Zeki, 1974;

Zihl et al., 1983) and is dominated by efferent projections from the M system. Tasks examining this aspect of the visual system will be outlined in the next section.

3.5 Motion Detection Impairments in Dyslexics

The two tasks used most frequently to assess sensitivity at V5 in studies of dyslexia are speed discrimination and coherent motion tasks. In a speed discrimination task, participants view two successive stimuli. One is a baseline stimulus moving at a set speed (e.g., 20.8 deg/s). The other is a test stimulus with a variable speed that is always above the speed of the baseline stimulus. The task is to report which of the stimuli moves the fastest. The contrast and duration of the stimuli are selected at random so participants have to base their responses on speed alone (Demb, Boynton, Best & Heeger, 1998).

In two studies, Demb and colleagues (Demb, Boynton, Best et al., 1998; Demb, Boynton & Heeger, 1998) assessed groups of control and dyslexic adult readers ($n = 5$) on tests of speed discrimination. The dyslexic group were found to have higher psychophysical thresholds than the control group for speed discrimination, indicating less sensitive M systems (Demb, Boynton et al., 1998). Using fMRI technology, the dyslexic group also showed reduced brain activity both in V1 and the V5 complex, which receive primarily M system afferents (Demb, Boynton et al.). The results were interpreted as support for an M system abnormality in dyslexia. A more recent study has replicated speed (referred to as velocity) discrimination deficits in a larger sample of dyslexics (Wilmer, Richardson, Chen & Stein, 2004). Using adults, Wilmer et al. (2004) compared dyslexic ($n = 19$) and control ($n = 17$) groups on a speed discrimination task. The results demonstrated that the dyslexic group had significantly higher speed discrimination thresholds than the control group. This effect remained significant even when variance attributable to IQ was statistically removed. Thus, there

is evidence to demonstrate a speed discrimination deficit (linked to the V5 complex) in dyslexic groups.

The second type of task used to assess activation in V5 is typically referred to as a coherent motion task. In these apparent motion tasks, random dot kinematograms (RDKs) are generated on a computer screen. In a typical RDK, a proportion of the total pixel elements (dots) move in a coherent manner, while the remainder move in a random fashion. The effect is to generate perception of global coherent motion (Stein, 2003). In a given trial the duration of the entire stimulus is determined by the number of computer animation frames presented. The lifetime of each dot within the stimulus is limited by ensuring each dot only lasts for a certain number of animation frames before disappearing and reappearing at random positions within the stimulus patch (Talcott, Hansen, Assoku & Stein, 2000). By limiting the lifetime of each dot, viewers are prevented from detecting motion by tracking the movement of a single dot. Instead they have to make a decision regarding global motion perception, which is achieved by summation of the physiological activation of individual motion detectors within the V5 complex (Talcott, Hansen et al., 2000). Thresholds for coherent motion detection are determined by the smallest percentage of dots required to be moving coherently to correctly detect the global motion. The lower the individual's threshold, the more sensitive they are to global coherent motion.

Previous studies have used two classes of coherent motion tasks. In a single panel task (e.g., Raymond & Sorensen, 1998), participants are presented with a single patch of dots that move coherently left or right. The task is to report the direction of motion (left or right). The second type of coherent motion task is a double panel task, the most frequently used of which was developed by Hansen et al. (2001). In this task, participants view two dot patches presented side by side. In one patch, the apparent movement of the dots is random. In the other patch, the dots move in a coherent left-

right manner. The task requires participants to identify the patch that contains the coherent left-right motion. The double panel task (Hansen et al.) also includes the use of catch trials to assess vigilance. Catch trials have a percentage of coherently moving dots that is well above the participant's threshold for motion detection. As the participant should be able to respond correctly with ease, poor performance on the catch trials is taken as evidence of lack of vigilance or random responding. Both tasks have been shown to discriminate between dyslexic and control groups. However, when all other variables are held constant, the double panel task is thought to be perceptually more difficult and, in general, to discriminate better between groups (Stein, 2003). Data is also available on the internal consistency of this task, which makes it more amenable to use in research. Talcott et al. (2002) demonstrated a high correlation ($r = .70$) between successive threshold estimates for the Hansen et al. (2001) double panel task in an unselected sample of 350 primary school children, indicating adequate inter-block reliability. Wilmer et al. (2004) also reported a high degree of reliability ($r = .80$) for successive threshold estimates collected within a single testing session for this task in adult dyslexics and controls.

Research has also shown that stimulus parameters are important in discriminating between the motion detection sensitivity of dyslexic and control groups. Talcott, Hansen et al. (2000) obtained motion detection thresholds on a single panel task in groups of dyslexic ($n = 10$) and control ($n = 10$) adult readers, while varying the temporal and spatial properties of the apparent motion stimulus. Results showed that lengthening stimulus duration or increasing the dot size did not improve the performance of the dyslexic group. However, increasing the density of the dots within the stimulus patch had a significant positive impact on the thresholds of the dyslexic group. In fact, there was no difference between dyslexic and control group thresholds when dot density was equal to or greater than 12.2 dots/deg². If we accept the argument

that dyslexics have a similar deficit in the organisation and structure of cells within V5 as has been found in the M layers of LGN (e.g., Stein, 2003; Talcott et al., 2003) these data can be explained in terms of the cellular structure and function of V5. Individual cells in V5 are tuned to a specific direction of motion in a particular section of the visual field. If the summed responses of the individual cells exceed a given critical threshold, the visual system can perceive global motion in the stimulus. In V5 in dyslexic brains the global motion signal may not exceed this critical perceptual threshold when the stimuli are spatially diffuse stimuli such as in RDKs with low dot density. However, in high dot density RDKs the number of individual elements signalling motion at a given coherence level is much greater than in low density RDKs. Therefore, a greater number of individual motion detector cells are activated across a wider area. Consequently, the total global motion signal may exceed the critical threshold despite the proposed cellular dysfunction in dyslexic brains. On the basis of these results, it can be seen that a subtle impairment in motion detection at V5 in dyslexics can only be detected when the dot density of the RDK stimulus is below 12 dots/deg².

In the first study to investigate motion processing in dyslexics, Cornelissen et al. (1995) assessed coherent motion thresholds using a double panel task in groups of dyslexic children (n = 29) age-matched controls (n = 29). The participants performed the coherent motion task four times so that four separate thresholds were obtained. The dyslexic group had significantly higher motion detection thresholds than the control group regardless of which threshold, or combination of thresholds was used. This was the first evidence of a visual deficit in the cortical visual system at V5 and was interpreted as further evidence of reduced M system sensitivity in dyslexics. However, the effect size for the combination of all four thresholds (Cohen's $d = .46$) was in the small to moderate range demonstrating overlap between the groups, and visual inspection of the data (Cornelissen et al., 1995) also demonstrated substantial overlap

between groups on all threshold measures. No individual data or reliability statistics were reported so it is unclear if the same dyslexics were responsible for the significant effects at each of the different threshold measurements. In the same study, Cornelissen et al. demonstrated that significant motion detection impairments could also be found in a group of dyslexic adults. The effect size for the adult data was within a similar range to that found experiment conducted with children (Cohen's $d = .46$).

Impairments in coherent motion detection in groups of dyslexic children have since been replicated in a number of different laboratories (Pammer & Wheatley, 2001; Raymond & Sorenson, 1998; Ridder, Borsting & Banton, 2001; Slaghuis & Ryan, 1999) and across cultures (Talcott et al., 2003). For example, Talcott et al. tested groups of dyslexic ($n = 19$) and skilled reading ($n = 22$) Norwegian children on the task used by Hansen et al. (2001). On average the dyslexic group were significantly less sensitive to motion than the control group of skilled readers. Norwegian written language is phonetically regular (i.e., it does not contain words that cannot be decoded using regular sound-letter rules). Therefore, this data demonstrates visual impairments are not confined to children learning to read in English, which contains many irregular spelling patterns.

Coherent motion detection deficits have also been observed in groups of adult dyslexics (Conlon et al., 2004; Everatt, Bradshaw & Hibbard, 1999; Hansen et al., 2001; Hill & Raymond, 2002; Pelli & Zhang, 1991; Talcott, Hansen et al., 2000). For example, Conlon et al. (2004) reported that a group of dyslexic adults were significantly less sensitive to motion on a single panel task than a control group (Cohen's $d = .95$). In a separate experiment, they demonstrated that another dyslexic group were also less sensitive than a control group on the double panel task used by Hansen et al. (2001; Cohen's $d = 1.26$). These effect sizes are stronger than obtained from the earlier work by Cornelissen and colleagues (Cornelissen et al., 1995). It is unclear why this is the

case, however, it may reflect the development of the tasks designed to measure motion detection over time.

There is also evidence that the cortical visual impairment in dyslexics is specific to processing dynamic speed and motion stimuli at V5. Hansen et al. (2001) compared the performance of 15 dyslexic and 34 control adult readers on three visual processing tasks. Motion detection thresholds were obtained using a double panel coherent motion task. Although visual inspection of the data indicated there was substantial overlap in the thresholds of the two groups, a significant between group difference was reported, with the dyslexic group showing less sensitivity to global coherent motion.

Two measures of static global pattern processing were also obtained. In the first, the position of the target was fixed, while in the second, the position of the target was presented at random within the array. In both tasks, participants were required to detect a global circle pattern formed by line segments embedded in noise (randomly orientated line segments). These form detection tasks are thought to measure processing within the form sensitive area V4. The dyslexic group had similar thresholds to the control group on the fixed form processing task. In the randomised form detection task, the trend was for the dyslexic group to have higher thresholds ($p = .07$), but the difference in thresholds was not statistically significant. No effect size data was available from this study.

Some support for a selective motion processing deficit has also been provided by a more recent study. Wilmer et al. (2004) compared the performance of groups of 19 adult dyslexics and 17 control readers on the double panel coherent motion task and the fixed form processing task employed by Hansen et al. (2001). The dyslexic group were significantly less sensitive to motion than controls and the effect size (Cohen's $d = .90$) was large and replicates the effects reported by Conlon et al. (2004). In contrast, no significant between group differences were observed on the fixed form processing task

(Cohen's $d = .10$). Taken together, these results suggest the deficit at V5, seen behaviourally in elevated motion detection thresholds is specific to that area.

The adult data reviewed above indicates the impairments in motion detection observed in children are not the result of a simple delay in development of the neural systems responsible for motion detection, because the reduction in motion sensitivity in dyslexics continues in adulthood. The finding that dyslexics show less activation at V5 using fMRI technology when they view moving stimuli is also consistent with an impairment at V5 (Demb, Boynton et al., 1998; Eden et al., 1996). Taken together these studies support the proposal of impairment in the motion specialised area V5, which may be the result of impoverished M inputs from lower levels of the visual system. However, like the auditory theories of dyslexia presented in the preceding chapter, the magnocellular theory has been criticised for a number of reasons.

Thresholds for coherent motion have been shown to be a strong discriminating variable between dyslexic and control groups (e.g., Conlon et al., 2004; Hansen et al., 2001; Slaghuis & Ryan, 1999; Talcott et al., 2003). However, a number of studies have failed to find significant between group differences using coherent motion tasks (Edwards et al., 2004; Hill & Raymond, 2002; Kronbichler, Hutzler & Wimmer, 2002). For example, Kronbichler et al. (2002) tested groups of dyslexic ($n = 20$) and skilled reading ($n = 20$) German children on the double panel coherent motion task used by Hansen et al. (2001). To qualify for inclusion in the dyslexic group, children had to score below the 10th percentile on measures of spelling and reading fluency (a sensitive measure of reading difficulty in transparent orthographies) in both Grade 3 and Grade 7. Exclusionary criteria of non-verbal IQ < 85 was also applied. A range of data available from school entry testing showed the children in the dyslexic group also had phonological impairments.

Results showed thresholds for coherent motion in the dyslexic group did not differ significantly from control thresholds (Cohen's $d = .04$). Procedural and task parameter differences cannot account for these results because the same task and task procedures were employed as had been used in a number of previous investigations (Conlon et al., 2004; Hansen et al., 2001; Talcott et al., 2003). A number of other factors may explain the results. Firstly, the dyslexic group were significantly older than the control group. While global motion sensitivity appears to be well developed by age four (Braddick et al., 2003), the influence of other cognitive factors that develop with age cannot be ruled out. Secondly, IQ data was not presented for either the dyslexic or control group. The only information supplied to the reader was that members of the dyslexic group had non-verbal IQ > 85 . As IQ is known to be significantly related to psychophysical task performance (e.g., Conlon et al., 2004; Witton et al., 2002) it is difficult to make firm conclusions from this study without IQ data.

The null results found by the two other studies cited above (Edwards et al., 2004; Hill & Raymond, 2002) can be explained by the task parameters employed. For example, Hill and Raymond (2002) found that no significant differences existed between the thresholds of groups of dyslexic ($n = 7$) and control ($n = 7$) adults on a single panel task with stimulus duration of 133 ms (Cohen's $d = .26$) or when stimulus was 333 ms (Cohen's $d = .02$). However, the sample (dot) density used was 45 dots/deg². This is more than three times the density at which Talcott et al. (2000) found that there were no differences between the motion detection thresholds of dyslexics and controls. Edwards et al. (2004) also employed a coherent motion task in which the sample density (30 dots/deg²) was well above the level at which dyslexic and control groups can be separated. Therefore, neither of these studies can be considered to have employed tasks capable of detecting a subtle motion deficit in the dyslexic group. When Hill and Raymond (2002) employed a more difficult bi-directional transparent

motion stimulus task in which participants viewed two transparent sheets of dots moving coherently in two different directions, they were able to detect impairments within the dyslexic group (Cohen's $d = 1.17$). The strength of the group difference is also comparable to the results of Conlon et al. (2004) and Wilmer et al. (2004) in adults and provides additional evidence for the reliability of findings of motion detection deficits in dyslexic groups when appropriate stimuli are employed.

In addition to criticism based on failures to replicate, the magnocellular theory can be criticised for placing too much emphasis on p values as measures of significance, rather than examining effect sizes and individual data in addition to group means. Only two studies (Conlon et al., 2004; Wilmer et al., 2004) have presented effect size data in their published papers. Furthermore, although the majority of published studies have reported impairments within dyslexic groups, when individual data are examined it is evident that only a sub-group of dyslexics have impairments. It is also evident that at least a small number of control participants appear to be impaired on motion detection tasks. For example, the study conducted by Talcott et al. (2003) on Norwegian children demonstrated that on average the dyslexics were less sensitive to motion than controls. However, there was substantial overlap between the thresholds of the two groups. Indeed, when coherent motion thresholds were used to predict group membership in a discriminant function analysis they could correctly classify participants only at chance levels (52.6%). Furthermore, at least two control children had thresholds well above the poorest scoring dyslexic participant, indicating substantially impaired performance.

One additional argument that could be made is that difficulty maintaining vigilance during task performance can explain the presence of reduced sensitivity in dyslexic groups. Indeed, one recent study (Davis, Castles, McAnally & Gray, 2001) has argued lapses in concentration can explain the reduced sensitivity observed in dyslexics on an alternative apparent motion task: the Ternus task (Cestnick & Coltheart, 1999).

However, when Davis et al. conducted an experiment in which the concentration demands and length of the Ternus task were reduced, perceptual differences between dyslexic and control groups were still evident. That is, the dyslexic group was still impaired in perception of apparent motion even when the possible effects of vigilance were minimised. Most recent studies using coherent motion paradigms also employ catch trials (trials in which the coherence is well above threshold) to check for vigilance. They typically find that no differences exist in the vigilance of dyslexic and control groups (e.g., Conlon et al., 2004). It therefore seems unlikely that poor vigilance can completely explain motion detection impairments in dyslexics.

3.6 The Role of Motion Processing in Reading

Given the importance of visual processing skills, such as visual feature analysis, attention to visual detail, and visual pattern analysis to orthographic coding (Vellutino et al., 1994), it comes as no surprise that it has been hypothesised that motion processing is related to orthographic coding ability. For example, Cornelissen, Hansen, Hutton, Evangelinou and Stein (1998) demonstrated there was a significant positive relationship between motion detection thresholds and the number of letter errors on a word reading task in an unselected sample of children ($n = 58$). Letter errors refer to pronunciations containing letters not in the target word (e.g., victim 'vikim'; temper 'templay'). In contrast, there was no correlation between motion detection thresholds and phonological skill (spoonerisms) or single word reading ability.

These findings were extended by Cornelissen, Hansen, Gilchrist et al. (1998), who compared 24 'good' and 24 'poor' coherent motion detectors matched for reading ability, age and IQ, on a task in which performance depended on accurate letter position encoding (a lexical decision task). In the lexical decision task, participants were presented with five-letter words or anagrams of five-letter words (e.g., FINAL; FNIAL).

The anagrams were generated by swapping the positions of two of the internal letters in the five-letter words. Poor motion detectors made significantly more errors for anagrams than good motion detectors, but no significant between group differences were observed for the real word stimuli.

The authors argued for an association between motion detection and accurate letter position encoding, which could affect the development of orthographic coding skills. It was proposed that this effect could be mediated by low-level M system deficits, or by higher-level attention processes which affect the ability to correctly bind the features (letters) of words (Cornelissen, Hansen, Gilchrist et al., 1998). A limitation of this research is that there is no way of knowing if the higher frequency of letter errors in the “poor” motion detection group was attributable to poor motion processing or simply to the type of reading strategy used by poor motion processors.

A more recent investigation has provided some support for the earlier work of Cornelissen and colleagues by demonstrating motion sensitivity is related independently to orthographic skill (Talcott, Witton et al., 2000). Participants were a small, unselected sample of children ($n = 32$). Orthographic processing was defined by taking the first principal component of performance on two tasks: exception word reading and a pseudohomophone task. Phonological skill was defined as the first principal component of performance on nonword reading and spoonerism tasks. After accounting for IQ, only coherent motion thresholds accounted for unique variance in orthographic skill (20%). In contrast, coherent motion thresholds were not a significant predictor of phonological skill. However, the independent nature of this relationship has not been replicated in a larger, more heterogenous sample (Talcott et al., 2002).

Talcott et al. (2002) examined the relationships between phonological and orthographic skill and visual processing in an unselected sample of 350 children. Phonological skill and orthographic processing was defined in the same way as in the

previous investigation (Talcott, Witton et al., 2000). Coherent motion thresholds accounted for significant portions of the variance in phonological skill (3%), orthographic skill (7%) and a component literacy measure (word identification and spelling skill; 3%) after the effects of IQ and catch trial (vigilance) performance were removed from the analysis. The relationship between motion processing and reading is therefore more complicated than an M deficit interfering with the ability to recognise specific visual word patterns when reading.

Evidence for an independent relationship between orthographic coding and motion detection has also been questioned by studies that have reported significant relationships between coherent motion detection thresholds and phonological skill. For example, in a study of groups of 18 dyslexic adults and 18 control readers, Talcott et al. (1998) found weak to moderate correlations between motion sensitivity and a phonological processing measure (nonword reading accuracy) within both dyslexic ($r = -0.4$) and control readers ($r = -0.356$). Nonword reading accuracy was more highly related to a combined measure of M system sensitivity, which included thresholds for coherent motion and a critical flicker fusion task ($r = .69$). Witton et al., (1998) have also reported significant correlations between nonword reading accuracy ($r = - .347$) and nonword reading time ($r = 0.541$) and processing dynamic visual motion in dyslexic and control adult readers.

Relationships between coherent motion thresholds and word identification skills have also been found. In an initial experiment, Conlon et al. (2004) found that motion detection thresholds could account for 26% of the variance in word identification skills in dyslexic and control adult readers. In a second experiment, they showed motion detection thresholds continued to account for a significant portion (19.5%) of the variance in word identification skills after accounting for general ability and auditory short-term memory. Conlon et al. argued that it might be reading skills in general that

are related to visual processing, rather than specific reading sub-skills. The ability to process temporal information such as motion stimuli may form a normal distribution similar to that which occurs for reading skills (Fletcher et al., 1994; Shaywitz et al., 1992; Stanovich & Siegel, 1994).

3.7 Summary

As evidence of a specific visual impairment in dyslexia, higher thresholds and reduced activation within V5 in response to moving stimuli have, on the whole, provided stronger evidence of a deficit than studies investigating processing in the retino-cortical visual system at LGN and V1. However, there have been some failures to replicate (e.g., Edwards et al., 2004; Hill & Raymond, 2002; Kronbichler et al., 2002); although only one of these studies (Kronbichler et al., 2002) used task parameters that could be considered adequate to assess a subtle cellular dysfunction at V5 in dyslexics. Currently, the most widely used task to assess motion sensitivity is the Hansen et al. (2001) motion coherence task. Given that there have been inconsistent findings presented in studies which have employed the same methodology (e.g., Kronbichler et al., 2002; Talcott et al., 2003; Hansen et al., 2001; Wilmer et al., 2004) the current study aimed to add to the literature by providing an independent external replication of current data using the Hansen et al. task in a large sample of dyslexic and control children. The study also aimed to incorporate an internal replication by measuring motion sensitivity in the same participants at separate points in time. An internal replication of data within a single study has not been attempted previously in the literature. This study was also interested in the mechanism by which poor motion detection could lead to reading difficulties. This aspect is particularly puzzling given that the cells of the P system have the fine visual resolution and visual discrimination properties necessary for the visual demands of reading (Vidyasagar, 2004). A number

of different theories have been put forward to explain the link between M deficits and reading, including: poor M-on-P inhibition (Breitmeyer, 1980; Breitmeyer & Ganz, 1976), poor eye movement control (Cornelissen & Stein, 1992; Fowler, 1991; Stein & Fowler, 1980; 1981; 1985; Stein, Fowler & Richardson, 2000; Stein, Riddell & Fowler, 1988), and impaired visual attention (Hari, Valta & Uutela, 1999; Vidyasagar, 1999; 2004). Of these theories visual attention has received the most recent attention and this study will focus on this area. Chapter 4 will review the evidence for visual attention impairments in dyslexics and also for the link between the M pathway and attention.

4.0 Dyslexia as a Disorder in Visual Attention

4.1 What is Visual Attention?

Several basic components are involved in visual attention. Some of these include: covert attention, which refers to switching on attention in response to a visual cue in preparation to detect a target; spatial allocation of attention to a particular location in the visual field; maintaining focus on the attended object; suppressing information from other areas of the visual field to avoid intrusion of irrelevant stimuli and; disengaging attention in preparation for processing new information (Steinman, Steinman & Garzia, 1998). Research has demonstrated that dyslexic groups have difficulty with a number of these aspects of visual attention relative to control groups (e.g., Heiervang & Hugdahl, 2003; Vidyasagar & Pammer, 1999). As the M system provides the dominant input to visual attention areas in posterior parietal cortex (PPC; Husain, 1991), some have argued that visual attention deficits are the result of impairments within the M system (e.g., Hari, Valta & Uutela, 1999; Vidyasagar, 1999; 2004). The evidence for visual attention impairments in dyslexics and the evidence that these deficits can be attributed to poor M system function is reviewed below.

4.2 Visual Attention Impairments in Dyslexics

Research has demonstrated that dyslexic groups have more difficulty than control groups with the inhibition aspect of attention (Bednarek et al., 2004; Facoetti, Paganoni & Lorusso, 2000). In experimental tasks this tends to lead to peripheral stimuli interfering with processing of focal stimuli. For example, Bednarek et al. (2004) tested groups of dyslexic and control children on the Attentional Network Test (Fan, McCandliss, Sommer, Raz & Posner, 2002). In this task a fish appears on a computer

screen either above or below a fixation cross. The task is to report which direction (left or right) the fish is facing. In some trials a visual cue is given to the intended location of the fish prior to presentation, while in other trials no cue is given. In alternative conditions, the target fish can also be accompanied by two 'flanker' fish that appearing to the left or right of the target. The flanker fish can be incongruent (facing the opposite direction to the target) or congruent (facing the same direction as the target).

The dyslexic group made significantly more errors than the control group in the incongruent flanker condition, indicating that the peripheral stimuli interfered with processing of the target. Facoetti et al. (2000) have also demonstrated that the dyslexic group were better able to identify visual targets at varying degrees of visual angle from the focus of vision than the control group. Together these data indicate that dyslexic groups have a wider distribution of visual-spatial attention than control readers and are less able to inhibit processing of irrelevant stimuli (Bednarek et al., 2004).

Dyslexic groups have also been shown to have visual attention impairments using the cue-target paradigm (Posner, 1980), which measures the ability to covertly activate attention in response to a visual cue. In this task, reaction time to accurately respond to the appearance of a target (e.g., a letter or an asterisk) on a computer screen is measured. The target appears randomly in the left (LVF) or right (RVF) visual field and is preceded by a visual cue in 80% of the trials, either in the same (valid cue) or opposite visual field (invalid cue). The shortest reaction time is observed for valid cue targets because performance is facilitated by a covert shift of attention, thought to be mediated by the M system (Hugdahl & Nordby, 1994; Posner & Peterson, 1990).

In a small study of groups of dyslexic ($n = 6$) and control children ($n = 6$) Brannan and Williams (1987) demonstrated that the groups had similar response accuracy for invalid cue trials. However, the dyslexic group made more errors in identifying targets in the valid cue condition. This inability to utilise visual cue

information was interpreted as being the result of a sluggish M system impairing the ability to make a covert shift of attention in response to the cue. However, the results have not been replicated in larger studies that have used reaction time rather than response accuracy as the measure of covert attention (Jonkman, Licht, Bakker & Van den Broek-Sandmann, 1992; Heiervang & Hugdahl, 2003). For example, Jonkman et al. (1992) found a group of dyslexic children performed more slowly than a control group across all cue conditions, not just when valid cue information could be used to facilitate rapid target identification. Heiervang and Hugdahl (2003) presented similar findings. They demonstrated that a group of dyslexic children ($n = 25$) had significantly longer RT than a control group ($n = 25$) for both valid and invalid cue conditions in a cue-target paradigm. Importantly however, there was a clear facilitation of response time for the dyslexic group in the valid cue condition, indicating they were able to make a covert shift of attention in response to the cue. The authors argued that this facilitation indicated that sensory processing was intact and that slower task performance could not be attributed to M system deficits. Rather, the authors suggested that the dyslexic group had greater limitations than the control group in the cognitive resources necessary for task performance.

A recent study has also questioned the role of the M system in the covert attention impairments previously reported in dyslexic groups using the cue-target task (Roach & Hogben, 2004). Roach and Hogben demonstrated that a small group of dyslexic adults ($n = 5$) had significantly slower reaction time than controls in the valid cue condition of the cue-target paradigm, indicating they were less able to make a covert shift of attention in response to the cue. In a subsequent experiment, the same dyslexic group were found to perform in a similar fashion to the control group on a flicker contrast sensitivity task (using low spatial and high temporal frequency stimuli known to maximally stimulate the M pathway), and a coherent motion task. These

results were interpreted as evidence against the involvement of the M system in the covert visual attention deficits seen in dyslexic groups (e.g., Brannan & Williams, 1987; Heiervang & Hugdahl, 2003; Jonkman et al., 1992).

In addition to difficulties in making covert shifts of attention in response to a visual cue, dyslexic groups also appear to be impaired in their ability to disengage attention from a visual stimulus (Hari et al., 1999). A measure of this ability can be found in the attentional blink task. Attentional dwell time refers to the time it takes to disengage attention from a stimulus and re-establish attentional focus on a subsequent stimulus. Attentional dwell can be quantified by measuring the duration of the 'attentional blink' in a task where participants first have to identify a target letter in a letter string and then detect another target appearing in close temporal succession. Hari et al. (1999) demonstrated the attentional blink of a dyslexic group was on average ~30% longer than in the control group. That is, identification of a visual stimulus occupied their attention for significantly longer than in the control group. As the M system is important for capturing covert attention, prolonged attentional dwell time in the dyslexic group was attributed to inefficiency in the M system in re-engaging attention when new stimuli arrive. However, the hypothesis for the involvement of the M system was speculative and no data was available on the visual processing abilities of the participants.

Most importantly for the current study, dyslexic groups have also been reported to have difficulty with visual search (Iles, Walsh & Richardson, 2000; Vidyasagar & Pammer, 1999; Wright & Conlon, submitted a). According to the literature on visual search (e.g., Triesman, 1988), when a target object differs from distractors on a salient and unique dimension (e.g., a single straight line among a number of lines oriented at 15°) target search occurs pre-attentively and in parallel across the visual field with number of distractors having no effect on search times (see Figure 2). In contrast, when

a target differs from distractors only by a conjunction of features (a yellow triangle among a number of purple triangles and yellow squares), or when the unique feature of the target is not salient (a circle with a small gap in its circumference among a number of circles), target search requires focused attention on each item in turn across the visual field. In serial search, search times are a function of the number of distractors in the display (see Figure 3; Triesman & Gelade, 1980). It has been proposed that at any given point in time when performing serial target search, a spotlight of attention focuses on a specific object in the visual field. This spotlight is proposed to have two basic functions. Firstly, it works to highlight an object in the visual field, prior to overt eye movements being made to the spatial location of that object. Secondly, by focusing attention on a single object, it allows the unambiguous binding of features from that object without interference from other objects (Triesman & Gelade, 1980; Triesman, 1988; 1993; 1996; Triesman & Gormican, 1988; Triesman & Schmidt, 1982; Triesman & Paterson, 1984; Triesman & Sato, 1990; Triesman, Viera & Hayes, 1992).



Figure 2. In parallel search, the target, which is unique and salient (the vertical line), is detected pre-attentively with number of distractors having no effect on search times.

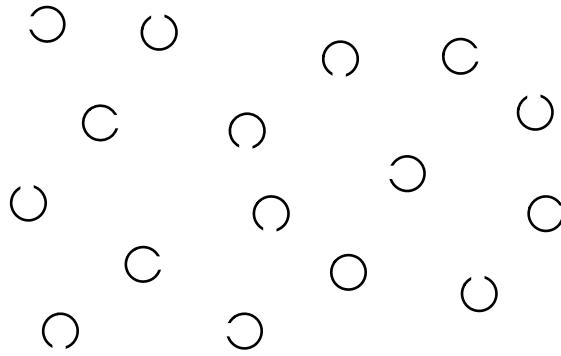


Figure 3. In serial search, the unique feature of the target (the circle) is not salient. Target search requires conscious attention and is conducted serially across the display.

Vidyasagar (1999) has proposed that the key to this attentional spotlighting mechanism lies in the functional properties of the M and P systems, speculating that the spotlight arises in PPC at the end of the M dominated dorsal stream. By taking advantage of the faster transmission rates and spatial coding properties of M cells the spotlight is able to provide feedback to a topographic map of the visual scene at V1. In doing so, it works to selectively highlight objects for more detailed processing in the P system and the ventral stream. This M dominated spatial selection mechanism would reduce the computational load on the system as a whole and enable the correct binding of object features crucial to perception because at any one time, only the features belonging to a single object would gain access to higher levels of processing in the ventral stream (Vidyasagar, 1999).

The importance of the M system to the attentional spotlight proposed to operate during visual search has been confirmed by two recent studies (Cheng, Eysel & Vidyasagar, 2004; Wright & Conlon, submitted b). Cheng et al. (2004) demonstrated that speed of serial search in a small group ($n = 4$) of adult participants was significantly slower when search items and background were isoluminant, than in search conditions in which even minimal luminance cues were available. Cells within the M

system are not selective for stimulus wavelength (colour), and are therefore severely inhibited under isoluminance conditions (Cheng et al., 2004; Zeki, 1993; Zeki & Shipp, 1988; Kaplan, Lee & Shapley, 1991). In contrast, M cells are extremely sensitive to even minimal luminance contrasts. These results therefore demonstrate the M system to be heavily involved in efficient serial search. Wright and Conlon (submitted b) replicated these results in a larger sample of adults ($n = 63$). Participants performed the serial search task presented in Figure 3 under luminance and isoluminance conditions. Speed of serial search was significantly slower in the isoluminance condition, demonstrating the importance of the M system to serial search.

Due to the importance of the M system and dorsal stream for efficient attentional spotlighting, Vidyasagar (1999) argued that dyslexics would show longer response times for serial search and make more errors in target identification because features from other spatial locations would interfere with feature binding. Vidyasagar (1999) also proposed that the functions performed by the M dominated spotlight are also crucial for reading processes, such as such as correct sequencing of letters within a word or words within a sentence. Thus, he argued that difficulty with the spotlight might provide the link between M deficits and dyslexia.

The model put forward by Vidyasagar (1999) led to a number of testable predictions. For example, a deficit in the M system should lead to poor visual search for serial search tasks that require the attentional spotlight, but not for parallel search tasks that are conducted pre-attentively. On the basis of this model, only individuals with M system deficits should be impaired at serial search. Finally, if the M system is responsible for poor visual search, there should be no differences in the search functions of individuals with and without M deficits when search stimuli are presented at isoluminance. A number of studies have now presented data that allow these predictions to be evaluated. For example, using a classic serial search task, in which

participants had to search for a target defined by a conjunction of two features (e.g., a yellow triangle among yellow circles and purple triangles), Vidyasagar and Pammer (1999) compared the visual search times of dyslexic ($n = 11$) and control children ($n = 9$). There were four search conditions involving 10, 24, 36 or 70 items.

The results demonstrated that the dyslexic group were impaired for serial search compared to the control group when there were a large number (70) of distractor items in the display (Cohen's $d = .78$). This was interpreted as being the result of impoverished M system inputs to visual attention areas in PPC. Vidyasagar and Pammer also argued that these data were consistent with the proposal put forward by Vidyasagar (1999) that attention deficits are the link between poor M system processing and reading. This conclusion appears to be based on the assumption that the dyslexic participants had an M system deficit. However, M system function was not assessed. It is therefore unclear whether the slower reaction time observed in the dyslexic group can be attributed to poor M system functioning, to a general visual attention deficit, or to some other cognitive variable associated with task performance.

There were also significant problems in subject selection methodology and reporting in the study by Vidyasagar and Pammer (1999). Control children were selected on the basis of teacher report of "average cognitive development" (Vidyasagar & Pammer, 1999; p. 1284). Therefore, it appears as if no formal testing of cognitive ability was conducted. The dyslexic children were reported to have normal cognitive development, although no specific data was presented. No data was presented on the reading skills of either group. By defining poor reading skills as a reading delay relative to the control group instead of the normative population provided in the test norms, Vidyasagar and Pammer (1999) may have included some children in the dyslexic group who were in fact average readers. Finally, only 14 of the original 21 children participated in the final 70 distractor condition in which significant between

group differences were observed. No data on the age, cognitive ability or reading ability of this small sub-sample was presented. It is therefore possible that the significant between group difference found in the 70 distractor condition was a result of inadequate matching on subject variables, rather than an M system, or visual attention impairment. Two additional studies have also demonstrated dyslexic groups are less efficient than control groups on serial search tasks requiring the M mediated spotlight (Williams, Brannan & Lartigue, 1987; Casco, Tessoldi & Dellantonio, 1998). However, both of these studies used alphabet characters as search stimuli. Therefore interpretation of slower visual search was confounded by lower reading ability and familiarity with letters in the dyslexic group.

The link between the M system and visual search performance has been investigated more directly by Iles et al. (2000). Two groups of adult dyslexics and a control group were assessed. One dyslexic group, referred to as the 'motion deficit' (MD) group, had previously been shown to be impaired on a coherent motion task (indicating poor M system function). The other dyslexic group, referred to as the 'non-motion deficit' (NMD) group had normal motion detection thresholds (indicating intact M system function). The dyslexics, who were diagnosed by educational psychologists, had poor word reading and poor phonological processing (nonword reading) and were closely matched to controls for cognitive ability.

Results demonstrated no significant between group differences for a parallel search task using different orientations. However, the MD group had significantly slower response times than the control group on a number of the serial search tasks. In contrast, the NMD group performed significantly more slowly than controls on only one serial search task. The NMD group also had significantly faster response times on all but two tasks compared to the MD group. The authors argued the results provided support for the hypothesis that magnocellular deficits can affect the ability to efficiently

allocate spatial attention during serial search. However, interpretation of the results is complicated by the observation that error rates for at least four of the eight tasks approached or exceeded chance levels (50% errors). Furthermore, as the NMD group had significantly slower response times than the control group on at least one serial search task and because the NMD did not perform significantly differently to the MD group on two serial search tasks, it is difficult to completely accept the presence of M pathway deficits (indexed by motion detection impairments) as the cause of poor visual attention performance in serial search in this study.

More recent data supports this conclusion. Wright and Conlon (submitted a) tested groups of control and dyslexic adults on serial and parallel search tasks under luminance and isoluminance conditions. The dyslexic group showed slower serial search performance as expected. However, they were also impaired for serial search at isoluminance, where the M system is severely inhibited. These data therefore question the involvement of the M pathway in the slower search times observed in the dyslexic group. The dyslexic group also showed significantly slower search times than the control group on the parallel search task, which did not require the M-mediated spotlight of attention proposed by Vidyasagar (1999). The authors concluded that the visual attention impairments seen in the dyslexic group were better described as general in nature, rather than specific to the M-mediated spotlight of attention. A limitation affecting interpretation of the results is that no measure of cognitive ability was obtained. Therefore, it could be argued that the generally poor performance of the dyslexic group was the result of cognitive differences between the reader groups.

4.3 Summary

Dyslexic groups appear to be impaired compared to controls across a number of visual attention tasks, including visual search. Vidyasagar (1999) has proposed a model

of visual attention that places an M-mediated attentional spotlight at an early processing stage. Vidyasagar proposed that this spotlight works to highlight areas for more detailed processing in the P or ventral systems and allows for unambiguous binding of object features without interference from objects in other spatial locations. Due to the putative role of the M system in controlling this spotlight Vidyasagar also proposed impairments would be observed in dyslexic groups for tasks such as serial search that require the spotlighting mechanism. Vidyasagar further argued that reading is also facilitated by the spotlighting mechanism by helping to correctly bind features within words and to correctly sequence letters within words, or words within a sentence. Visual attention may therefore be the link between the M system, reading and dyslexia. However, experimental evidence to support this conclusion is mixed. The three studies that have produced data against which Vidyasagar's model of visual attention can be evaluated have all demonstrated slow serial search in dyslexic groups (Iles et al., 2000; Vidyasagar & Pammer, 1999; Wright & Conlon, submitted a). However, the evidence for the critical role of a deficient M system in these deficits is inconsistent. All three studies could also be criticised on a number of methodological grounds. Further investigation of Vidyasagar's model of visual attention is therefore warranted.

This study initially aimed to replicate the previous data that has found significant differences between speed of serial search in dyslexic and control groups (Vidyasagar & Pammer, 1999; Wright & Conlon, submitted a). The external replication will provide additional evidence regarding the reliability of previous research results. By obtaining serial search data at two separate points in time this study will also provide important information regarding how reliably poor search performance can be replicated within the same participants across time. Previous studies have reported mean group differences without reporting the magnitude of the effect and without regard to individual data. The present study therefore aimed to investigate effect sizes and also to

perform a deviance analysis to determine the incidence of visual search impairments in the sample. Given the overlap typically seen for the sensory processing tasks that have been described in the preceding chapters it would be surprising if all dyslexics had visual attention deficits. Based on Vidyasagar's proposal this study also tested the following predictions: a) participants with serial search impairments will also have motion detection deficits, and b) dyslexics with motion detection deficits should be impaired at serial search relative to controls and also dyslexics who do not have motion detection impairments.

5.0 The Current Study

Research searching for the auditory and visual mechanisms underlying dyslexia has found that dyslexic groups are less sensitive than control groups to specific types of temporal auditory and visual stimuli (e.g., Hansen et al., 2001; Witton et al., 2002). A number of these studies have also found that auditory and visual processing thresholds account for significant portions of variance in reading skills measures (e.g., Conlon et al., 2004; Talcott, Witton, McLean et al., 2000; Witton et al., 2002). However, there have been a number of failures to replicate these data (e.g., Hari et al., 1999; Hill et al., 1999; Kronbichler et al., 2002), and the reliability of the findings of sensory processing deficits in dyslexic groups is yet to be fully established. One aim of the current study was to add to the literature by attempting to externally replicate the results of a number of recent investigations (e.g., Conlon et al., 2004; Hansen et al., 2001; Talcott et al., 2003; Witton et al., 2003) using the same sensory processing tasks. In addition, the present study aimed to conduct an internal replication by collecting sensory processing data from the same participants at two separate points in time. The present study is the first to investigate the stability of results across time. Specifically, it was predicted that the dyslexic group would be significantly less sensitive to measures of temporal auditory processing. However, they would be unimpaired for the non-temporal control variable 240 Hz FM. In the visual domain it was predicted that the dyslexic group would also be significantly less sensitive than the control group to detecting coherent motion. It was also predicted that significant relationships would be observed between measures of temporal processing, such as sensitivity to 2 Hz FM and coherent motion, and reading skills measures. The current study also focused on replicating measures of practical significance (e.g., effect sizes) in addition to replicating the results of measures of statistical significance (e.g., *p* values) from previous research. In addition to

examining between groups effects and measures of practical significance, the current study aimed to determine the incidence of sensory processing deficits in the dyslexic group. On the basis of previous research it was expected that only a sub-group of dyslexics would have impairments.

Another aim of the present study was to examine Vidyasagar's (1999) hypothesis that visual attention can explain the link between M system deficits and reading. Vidyasagar proposed that the inputs of the M system to visual attention areas in PPC are crucial for efficient functioning of an attentional spotlight, which is important for visual attention tasks and also for reading. This study examined visual attention in the dyslexic and control groups by administering a serial search task, which requires use of the attentional spotlight to direct attention in serial around the display (Triesman, 1980). It was predicted that only those dyslexics who had co-existing M system deficits (measured by poor performance on a coherent motion task) would show slow serial search performance.

To test these predictions, a longitudinal study was conducted in which the sensory processing, cognitive and reading skills of children initially identified as dyslexic and control readers were evaluated across a school year. All children who met initial criteria for inclusion in the study were assessed on a battery of cognitive, language, reading and sensory processing tasks at the beginning of the school year. During the course of the year, the dyslexic participants were engaged in school-based reading intervention programmes conducted in small group settings. The basic reading skills of all participants were assessed a further three times during the course of the year: once in each school term. In the final data collection phase, all participants were again assessed on the same battery of cognitive, language, reading and sensory processing measures administered at the beginning of the school year.

The use of this longitudinal design allowed investigation of two additional factors that have not been considered in previous research. Firstly, sensory processing skills were assessed in the same participants at two separate points in time. This allowed the study to determine if sensory impairments were stable across time, or whether an individual could perform poorly on one occasion and do well on another. Secondly, collecting thresholds at two points in time allowed the investigation of the test-retest reliability of the sensory processing measures employed.

5.1 Participants

Participants were recruited over a two-year period. The sample consisted of 252 students from 8 primary schools in South East Queensland and the Hunter Valley region of New South Wales. To select participants, class teachers from Grades 2 to Grade 6 were asked to identify students within their classes who were making satisfactory progress in reading and those students who were having difficulty with reading. Teachers were also asked to exclude children who met any of the following exclusionary criteria: (a) recurrent ear infections (b) severe hearing problems and uncorrected vision problems (c) severe emotional problems (d) English as a second language (e) diagnosis of attention-deficit hyperactivity disorder (ADHD) (f) diagnosed developmental disorder (e.g., Autism Spectrum Disorder). The parents of all selected children were contacted and asked for written permission for their child to participate in the study. They were informed that all participants would be evaluated at four stages throughout the school year on a range of reading achievement and ability tests, in addition to measures of sensory processing. Parents of struggling readers were informed that the information obtained in the first stage of assessment would be used to guide reading intervention for their child within the school.

In a second phase of initial screening all eligible participants were assessed on the Basic Reading Cluster (BRC) of the Woodcock Diagnostic Reading Battery (WDRB; Woodcock, 1997). The BRC is derived from the participant's scores on the Word Identification and Word Attack subtests. A participant scoring at or below the 15th percentile on the BRC was considered eligible for the dyslexic sample. To be eligible for inclusion in the control sample, participants had to score at or above the 40th percentile on the BRC. The use of these criteria has been suggested by Snowling (2000) and adopted by a number of studies (e.g., Vellutino et al., 1996). Participants who met the reading criteria were also assessed on the Coloured Progressive Matrices (CPM; Raven et al., 1995) as a standardised non-verbal measure of ability. To qualify for inclusion in the sample groups, participants had to have a standardised score of 90 or above on the CPM. The dyslexic participants were also required to be eligible for learning support lessons within their school. All the dyslexics received at least bi-weekly small group instruction in learning support classes, which focused on developing phonological skills and sound-letter links.

Using these criteria, 75 dyslexic children ($M = 8.5$ years; $SD = 1.4$ years) and 55 control children ($M = 8.5$ years; $SD = 1.25$ years) were selected for participation in the study. Forty-six of the dyslexic and thirty-four of the control children were male. The data from five dyslexic and three control children were subsequently removed from the sample because of excessive motor activity and inattention observed during testing. The performance of the remaining 70 dyslexic and 52 control participants on the selection measures is presented in Table 2. The study had Griffith University Human Ethics Committee clearance, which adheres to the guidelines of the National Health and Medical Research Council of Australia.

Table 2.

Selection measures including means and 95% confidence intervals.

	Control (<i>n</i> = 52)		Dyslexic (<i>n</i> = 70)	
Age (years)	8.58	(8.2 - 8.94)	8.62	(8.27 - 8.98)
IQ	106.93	(104.4 - 109.4)	104.54	(102.8 - 106.3)
WI	38.01	(36.04 - 39.9)	25.8	(24.1 - 27.5)
NW	17.9	(16.1 - 19.7)	6.5	(5.3 - 7.6)
BRC	494	(489 - 499)	458	(454 - 463)

Note. IQ = standard score on CPM, WI = Word identification raw score /57, NW =

Nonword reading raw score /30, BRC = W score Basic Reading Cluster.

5.2 Measures

5.2.1 Cognitive ability

The Coloured Progressive Matrices (CPM; Raven et al., 1995) consists of 36 trials involving abstract visual stimuli. All trials require understanding of the relationships between the stimuli and all are multiple choice. The easiest trials consist of a large pattern with a section missing. The participant is required to select one of four pieces that fits the larger pattern. In the more difficult trials participants have to select which of four options continues the logical pattern or progression formed by three symbols. The ability to solve visual analogies such as these has been shown to be an excellent measure of general intelligence (Kaufman & Kaufman, 1990; $r = 0.85$ to 0.90 for test-retest reliability).

5.2.2 *Phonological processing*

5.2.2.1 *Phonological awareness measures*

Phoneme elision

The Phoneme Segmentation subtest from the Dyslexia Screening Test (DST; Fawcett & Nicholson, 1996) was used as a measure of phoneme elision ability. The first part of the task requires deletion of syllables (say rainbow without the /bow/), blends (say stake without the /st/), and phonemes (say igloo without the /l/) from orally presented words. The second part of the task required the participant to transpose the initial phoneme in two orally presented words (spoonerisms). For example, Shirley Bassey becomes Birley Shassey. Each correct response received 1 point (maximum score = 15; $r = .883$ for test-retest). Hereafter this variable will be designated Phoneme Elision (PE).

Syllable blending, phoneme blending, rhyme oddity awareness, phoneme segmentation

The above abilities were assessed using selected subtests of the Sound Linkage Test of Phonological Awareness (Hatcher, 2000). On the syllable blending subtest participants had to blend orally presented syllables to form a word (win – dow becomes window). The phoneme blending subtest required participants to blend a string of orally presented phonemes to form a word (d-i-s-c becomes disc). The rhyme oddity subtest required participants to select the word that did not rhyme from a group of three orally presented words (dog pot log). The phoneme segmentation subtest required participants to segment orally presented words into their constituent phonemes (cost becomes c-o-s-t). Each correct response received 1 point (maximum = 24; $r = .94$ for

internal consistency). Hereafter this variable will be designated Phonological Awareness (PA).

5.2.2.2 Rapid automatised naming (RAN)

The RAN subtest from the DST (Fawcett & Nicholson, 1996) required participants to produce the name of 20 familiar objects presented as two-dimensional drawings on a card. The test provides the opportunity for the participant to familiarise him/herself with an untimed practice trial using identical stimuli to the test stimuli. Participants were asked to name the test stimuli as soon as possible following presentation without making mistakes. Performance was taken as the time to correctly name the entire test stimuli measured with a digital stopwatch ($r = .852$ for test-retest).

5.2.2.3 Phonological memory

The digits forward component of the Digit Span Subtest from the WISC-III (Wechsler, 1997) was used as a measure of phonological memory. Only the digits forward component was used because tasks that incorporate backwards recall of digits introduce complex cognitive processes which are undesirable if the purpose of the task is to provide a pure measure of phonological memory (Wagner et al., 1999). Recent research has shown phonological memory impairments reflect inaccurate encoding of the phonological characteristics of verbal information (Tijms, 2004). The digits forward component of Digit Span can therefore be thought of as a phonological processing task that is affected by the quality of an individual's phonological representations. In this task, participants are required to repeat a series of orally presented digits in correct presentation order. Each correct response received credit of 1 point (maximum score = 16; $r = .87$ for internal consistency, $r = .83$ for test-retest).

5.2.3 *Reading ability measures*

5.2.3.1 *Word identification*

The Word Identification subtest from the WDRB (Woodcock, 1997) was used to assess single word identification ability. The task required participants to orally pronounce single letters and words. The performance index for this task was the raw score for total number of letters and words correctly identified (maximum score = 57; $r = .944$ for internal consistency and $r = .948$ for test-retest).

5.2.3.2 *Nonword reading*

The participant's ability to use phonological information to decode words was assessed with the Word Attack subtest from the WDRB (Woodcock, 1997). The test required the participant to pronounce a series of nonsense words. As the nonsense words are not in the participant's lexicon, they have to be decoded, which relies upon knowledge of grapheme-phoneme links. The performance index for this test was the raw score for the total number of nonsense words correctly identified (maximum score = 30; $r = .916$ for internal consistency).

5.2.3.3 *Basic reading skills cluster (BRC)*

Scores on the Word identification and Word Attack subtests of the WDRB (Woodcock, 1997) were transformed into Rasch ability ("W") scores to obtain a composite score representing general reading ability that was used to evaluate growth in reading skills over the school year ($r = .962$ for internal consistency). The strength of using the Rasch-scale scores is that they are measured on an interval scale and particularly appropriate for assessment of individual change (Francis, Shaywitz, Stuebing, Shaywitz & Fletcher, 1996).

5.2.3.4 Oral reading proficiency

The Neale Analysis of Reading Ability – Third Edition (Neale, 1999) was used to evaluate accuracy in reading connected text orally. This test consisted of six passages arranged in increasing levels of difficulty. All participants began reading the first passage and continued with successive passages until they made more than 12 errors on a given passage or until the final passage was administered. A maximum of 16 points was allocated for each passage, except the final passage, which was allocated 20 points. The performance index for each passage was equal to 16 (or 20 for the final passage) minus the total number of errors made on that passage (maximum score = 100; $r = .81$ for internal consistency).

5.2.3.5 Orthographic coding

The Word-Pseudohomophone task (Olson et al., 1994) was used as a measure of orthographic skill. Stimuli were generated by the V-Scope software package (Enns & Rensink, 1992) on a Macintosh Power Mac with a standard monitor. Participants viewed two words presented side by side on a computer screen in 28 point Arial font. One was a high frequency word (e.g., take) and the other was a nonsense word with identical phonological output (e.g., taik). This task is considered a measure of orthographic coding because identification of the correctly spelt word requires the child to have an intact memory for the orthographic form of the word because no phonological cues are available for discrimination (Olson et al., 1994). Participants familiarised themselves with the task with a series of 10 practice trials. Eighty test items were then presented in four blocks of twenty trials. Feedback was given after each trial and the error rate was given at the end of each block. Participants were

instructed that they would see two words on the screen; both words would sound the same, but only one of them was spelt correctly. Their task was to point to the correctly spelt word. Responses were recorded by the experimenter on the computer keyboard. Split-half reliability for this task is .93 (Olson et al., 1994).

5.2.4 *Psychophysical measures*

5.2.4.1 *Visual coherent motion*

Thresholds for detecting coherent motion were measured using the double panel task developed by Hansen et al. (2001). Stimuli were displayed on a laptop PC with a 15-inch LCD screen. Two patches of 300 high luminance (130 cd/m^2) white dots (1 pixel) were presented on a black background (0.98 cd/m^2). One patch contained a variable percentage of dots moving in a coherent left-right manner, while the second patch contained only noise elements. For coherently moving dots the direction of motion reversed every 572 ms, with noise dots randomly changing direction in a Brownian manner with each screen refresh. To eliminate the possibility of tracking a single dot, the lifetime of each dot in the RDK was fixed at three animation frames (85ms) after which they disappeared and were regenerated at a randomly selected stimulus location within the same stimulus panel. Percentage of coherent motion was corrected for the finite lifetime of the dots. The percentage of target dots (angular velocity $7.0^\circ/\text{s}$) within a given software animation frame (28.6 ms) was varied to each participant's detection threshold from an initial starting value of 66.7% using a weighted one-up, one-down adaptive staircase technique (Kaernbach, 1991). For correct responses the motion coherence of the target stimulus was decreased by 1 dB (a factor of 1.122). For incorrect responses the proportion of signal dots was increased by 3 dB (a factor of 1.412). The staircase procedure was terminated after 10 reversals and

detection threshold was defined as the geometric mean of the final eight reversals. Catch trials in which coherent motion depth was the same as the starting coherency (66.7%) were included at random (at least once every five trials) during each block to evaluate participant vigilance. Two blocks of test trials were conducted. The threshold of greatest sensitivity was taken as the participant's motion detection threshold.

Binocular viewing of the RDK patches was conducted in a darkened room where lighting was held constant at ~ 5 cd/m². All participants were light adapted prior to presentation of the task. Each patch subtended $10^\circ \times 14^\circ$ of visual angle and the patches were separated horizontally by 5° visual angle at a viewing distance of 57 cm held constant by a chinrest. The stimulus program randomly generated the patch containing coherent motion. Stimulus duration for each trial was 2.3 seconds. Participants were instructed to inspect the two stimulus patches (see Figure 4) and report which patch contained coherent motion (“which had the dots moving side to side”) by pointing with their finger or saying “left” or “right”. Responses were recorded by the experimenter on the computer keyboard. Feedback was given by means of a high (correct) or low (incorrect) tone after each response. Each participant completed five practice trials before testing began. The coherence depth for the practice trials was fixed at a value well above the average threshold for all participants. If the subject made an error on the practice trials, practice testing continued until the criteria of five trials in a row correct was met.

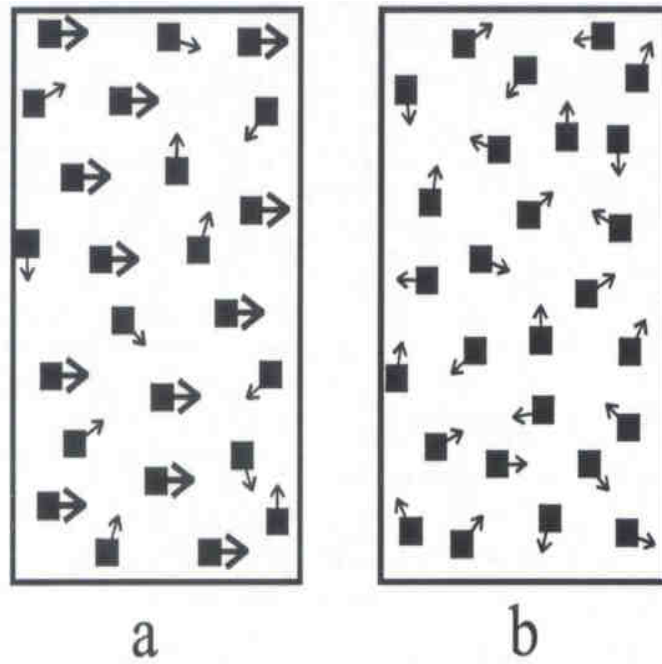


Figure 4. Example of task stimulus for coherent motion task. In the first panel (Panel a), a percentage of the dots are moving in a coherent left to right manner. In the second panel (Panel b), the dots move in a random manner (Hansen et al., 2001).

5.2.4.2 Psychoacoustic measures

Thresholds for the detection of four types of sinusoidal frequency and amplitude modulations of a 1 kHz tone were measured (Witton et al., 2002). The target stimuli were either: 2 Hz FM, 240 Hz FM, 2 Hz AM or 20Hz AM. Sensitivity for each of these acoustic stimuli was assessed in separate tasks. The acoustic stimuli were generated using DirectX7 software on a laptop PC. For each trial, two tones of 1000 msec duration were presented. One was a pure tone and the other was the modulated (target) tone separated by an ISI of 500 msec. The interval containing the target tone was selected at random by the stimulus program. All tones were gated with 20 msec cosine² rise and fall times and were presented at approximately 70 dB SPL through AKG K100 closed cell headphones. Each threshold measurement began with 5 practice trials where the modulation depth (the extent of the sinusoidal deviation of the

amplitude or frequency from that of the carrier; Witton et al., 2002) of the target tone was fixed at a value well above the average threshold for all participants. If an error was made on the practice trials, practice testing was continued until the participant made 5 correct responses in a row. For test trials the modulation depth of the target tone was adjusted to each participant's detection threshold using a weighted one-up, one-down adaptive staircase technique (Kaernbach, 1991). For each correct response the modulation depth was reduced by 1 dB and for each incorrect response the modulation depth was increased by 3 dB (Witton et al., 2002). The staircase procedure was terminated after 10 reversals and detection threshold was defined as the geometric mean of the final eight reversals. Catch trials in which the modulation depth of the target tone was the same as the starting coherency for each task were included at random (at least once every five trials) to evaluate participant vigilance.

While listening to the acoustic tones participants also viewed a display on the computer monitor. The computer display contained a blue and a green bird. The effects were such that the blue bird appeared to make the first sound and the green bird the second sound. Participants were instructed to listen to both sounds and then point to the bird (or say the colour of the bird if they preferred) that made the modulated sound. The experimenter recorded the participant's response by clicking the computer mouse on the bird the participant selected. Participants were informed that when they responded correctly, the bird would lay an egg for them. The goal of the task was to get as many eggs as possible. This procedure was highly motivating and enjoyable for the majority of children.

5.2.4.3 Visual reaction time task

This task measured simple motor reaction time in response to the presence of a visual symbol on a computer screen. Visual symbols were black circles subtending a

visual angle of 2° at 57 cm. A single circle could appear at any of eight random points on the screen. Stimuli were generated and randomised by the Vscope software package (Enns & Rensink, 1992) and were administered on a Macintosh Power Mac with standard computer monitor. Stimuli were presented on a grey background with space-averaged luminance held constant at 15 cd/m^2 . Participants were instructed to respond as soon as possible to the appearance of any visual symbol appearing on the screen by pressing the space bar. A block of five practice trials was given prior to the test trials to familiarise participants with the task. A block of ten experimental trials was then administered. Simple motor reaction time was defined as the mean of the response times for the ten trials.

5.2.4.4 Visual search

Targets were black circles and the distractors were circles with a gap located at randomly designated points on each circle's circumference. At a viewing distance of 57 cm, each circle subtended a visual angle of 0.5° with the gap for distractors subtending a visual angle of 0.15° . The target, present for half the trials, appeared randomly within the array. At Phase 1, in any one trial 4, 8, 16 or 32 items were presented. At Phase 4, in any one trial 8 or 32 items were presented. All displays subtended a visual angle of 12° vertically and 14° horizontally at a viewing distance of 57 cm, which was held constant by means of a chinrest. Stimuli were produced and randomised by the Vscope software package (Rensink & Enns, 1992) and were presented on a Macintosh Power Mac with standard computer monitor. Search stimuli were presented on a grey background with space averaged luminance held constant at 15 cd/m^2 . Figure 5 gives an example of the stimulus configuration used for serial search.

Participants were instructed to respond as soon as possible to the presence or absence of the target without error. If the target was present participants were instructed

to press a key marked 'P', or a key marked 'A' if the target was absent. Following a response, the stimulus was removed from the screen and response accuracy feedback in the form of a plus (correct) or a minus (incorrect) sign was displayed. A block of 20 practice trials was administered to familiarise participants with the procedure.

Participants were required to respond with at least 90% accuracy before proceeding to the experimental trials. In Phase 1, experimental trials consisted of four blocks of 16 trials with eight trials per condition. In Phase 4, experimental trials consisted of two blocks of 16 trials with eight trials per condition. Mean correct reaction times and accuracy data for the target present conditions were obtained. Room lighting was held constant at ~ 5 cd/m² and all participants were adapted to lighting conditions prior to beginning the task.

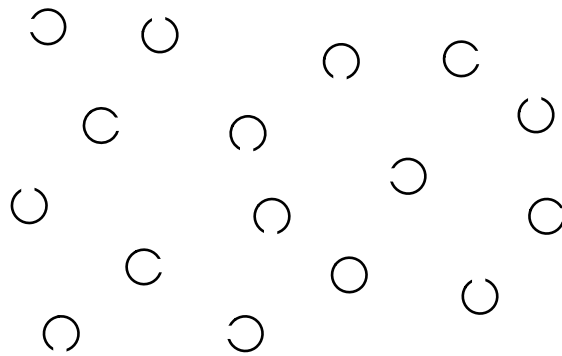


Figure 5. Stimulus configuration for serial search in 16-item condition.

5.3 Procedure

The same procedure was conducted for each of the cohorts in this study. All participants took part in four data collection phases separated by a period of ~ 10 weeks. During the first month of the school year (Phase 1) the entire test battery was administered to all participants. Administration was conducted in a quiet room at the participant's school, free from visual and acoustic distractions. The entire battery took approximately 1.5-2 hours to complete and was typically conducted in two sessions.

The second data collection phase (Phase 2) took place within the first two weeks of the second school semester. In this phase, all participants were administered the BRC (Woodcock, 1997). The same measure was collected within the first two weeks of the third school semester (Phase 3). The final data collection took place within the first month of the final school semester (Phase 4) and included the entire test battery outlined in the Measures section (excluding the CPM). Administration of all measures for Phase 4 took approximately 1.5 hours to complete and was typically conducted in at least two sessions. For the long test batteries conducted in Phases 1 and 4, the order of presentation of the psychophysical measures was counterbalanced across participants and regular breaks were taken between tasks.

5.4 Results and Discussion

5.4.1 Reading measures

Table 3 presents results for the additional measures of phonological processing, orthographic coding and oral reading accuracy at Phase 1. All assumptions of the analyses were met. The dyslexic group performed significantly more poorly than the control group on all tasks of phonological processing: Phonological awareness, $t(120) = 5.72$; $p < .0005$ (Cohen's $d = 1.09$), Phoneme elision, $t(120) = 6.97$; $p < .0005$ (Cohen's $d = 1.28$), Rapid automatized naming, $t(120) = -5.45$; $p < .0005$ (Cohen's $d = 1.21$), and Phonological Memory, $t(120) = 5.12$; $p < .0005$ (Cohen's $d = .88$). Compared to the control group, the dyslexic group also had significantly lower scores on the measures of oral reading accuracy, $t(120) = 7.77$; $p < .0005$ (Cohen's $d = 1.54$), and orthographic skill, $t(120) = 5.5$; $p < .0005$ (Cohen's $d = 1.04$).

Table 3.

Mean score and 95% confidence interval for additional reading measures at Phase 1.

	Control (<i>n</i> = 52)	Dyslexic (<i>n</i> = 70)
PA	21.2 (20.6-21.8)	18.3 (17.06-19.1)**
PE	10.3 (9.6-11.06)	6.9 (6.27-7.58)**
RAN	28.08 (25.5-30.6)	42.6 (38.46-46.85)**
PM	12.5 (11.7 – 13.2)	10.21 (9.65-10.7)**
Oral	51.1 (41.2-61.1)	20.3 (17.3-23.3)**
Ortho	60.5 (57.04-63.5)	50.7 (48.6-52.7)**

Note. PA = Phonological Awareness raw score /24, PE = Phoneme Elision raw score /15, RAN = Rapid Automised Naming mean response time (sec), PM = Phonological Memory raw score /16, Oral = oral reading raw accuracy score /100, Ortho = orthographic coding raw accuracy score /80.

** $p < .0005$

5.4.2 Summary reading measures

Previous research examining the relationship between sensory processing and reading has evaluated two independent components of reading ability: phonological processing and orthographic coding skill. In a similar fashion to these studies, the present study produced summary variables to represent the tasks thought to define these sub-components of reading. To summarise phonological processing skill for later analyses the *Z*-scores for the four phonological variables were averaged to produce a new variable designated PHONOLOGY. The raw scores for the orthographic task were also standardised so as to be directly comparable to the PHONOLOGY variable. This new variable was designated ORTHOGRAPHY. The method used in the present study to produce the summary reading variables followed that of two recent investigations (Huslander et al., 2004; Ramus et al., 2003). However, the method differs from the technique of generating a linear component from factor analysis used in a number of other previous studies (e.g., Talcott et al., 2002; Talcott, Witton et al., 2000; Wilmer et

al., 2004). Of these two methods, the z-score technique was selected to give equal weighting to each measure for further testing.

Although previous research (e.g., Talcott et al., 1998; Talcott et al., 1999; Talcott, Witton et al., 2000; Talcott et al., 2002) has examined phonological processing and orthographic coding ability separately, at least two arguments can be made against doing so. Firstly, many researchers believe they may actually be interconnected features in a complex reading system in which both orthographic and phonological information is required for word pronunciation (e.g., Vellutino et al., 2004; Vellutino et al., 1994). This argument is supported by findings of high correlations between orthographic and phonological task performance (Gough & Walsh, 1991; Talcott, Witton, McLean et al., 2000; Vellutino et al., 1994). The second argument is based on that of Conlon et al. (2004), who proposed that it may be reading skills in general that are related to visual processing, rather than specific reading sub-skills and that the ability to process temporal information such as motion stimuli may form a normal distribution similar to that which occurs for reading skills. To investigate if the reading measures in this study could be separated into independent components or if an overall reading measure could be created, all the reading measures collected at Phase 1 and Phase 4 were entered into two separate principal component analyses. For Phase 1 data, one factor emerged that accounted for 71% of the variance in the component variables (see Table 4). One factor also emerged at Phase 4, this time accounting for 68% of the variance in the component variables (see Table 4). A third summary variable was therefore created to reflect overall reading ability by averaging Z-scores for all PHONOLOGY and ORTHOGRAHY tasks plus Word identification, Nonword reading and Oral reading accuracy. This variable was designated READING.

Table 4.

Factor loadings for Phase 1 and Phase 4 reading measures. One factor was extracted – designated READING.

Task	Factor loading (READING)	
	Phase 1	Phase 4
Word identification	.95	.94
Word attack	.90	.87
Oral reading accuracy	.95	.92
Orthographic skill	.87	.86
PE	.86	.87
PA	.72	.6
RAN	-.72	-.75
PM	.75	.74

5.4.3 Sensory processing measures

5.4.3.1 Psychophysical task reliability

Inter-block reliability

Inter-block reliability provides a measure of the stability of thresholds within a single testing session. The correlations between two threshold estimates for each of the four psychoacoustic tasks ranged between .67 and .73, indicating adequate inter-block reliability. The correlations (Pearson's r) between two threshold estimates for the coherent motion task were .63 at Phase 1 and .71 at Phase 4. The strength of these correlations indicates the tasks had adequate inter-block reliability. The inter-block reliability in this study is similar to that reported by two recent studies (Talcott et al., 2002; Wilmer et al., 2004) for the same coherent motion task.

Test-retest reliability

Investigating the correlations between threshold measurements obtained at Phase 1 and Phase 4 provided an estimate of the test-retest reliability of the

psychophysical tasks. Five separate hierarchical linear multiple regression analyses were performed with Phase 1 threshold for each of the auditory and visual sensory processing tasks as the dependent measure. To control for the effect of differences in vigilance within the separate data collection sessions, catch trial performance at Phase 1 and Phase 4 was accounted for at Step 1 in the analyses. At Step 2, Phase 4 thresholds were entered as the independent variables. The partial correlation between Phase 1 and Phase 4 thresholds was taken as the estimate of test-retest reliability. The correlations are presented in Table 5. The strength of the correlations indicated there was moderate reliability in performance across time on the five psychophysical tasks administered ($r = .45 - .63$). As a comparison, Table 6 presents the test-retest reliability co-efficients (Pearson's r) between Phase 1 and Phase 4 for a number of reading skills measures. All of these measures had strong reliability across time and were substantially more stable than the sensory processing tasks.

Table 5.

Partial correlations between coherent motion and psychoacoustic thresholds for Phase 1 and Phase 4.

Task	Partial r ($n = 122$)
Coherent motion	.51
2 Hz FM	.6
240 Hz FM	.45
2 Hz AM	.63
20 Hz AM	.50

Table 6.

Reliability co-efficients (Pearson's r) for a number of reading variables between Phase 1 and Phase 4.

Task	Pearson's r ($n = 122$)
Word identification	.92
Word attack	.83
Oral reading accuracy	.95
Phoneme elision	.82

Although one could describe the moderate reliability of the sensory processing tasks as disappointing, it must be acknowledged that the task procedure for these tasks is susceptible to errant responses. That is, the tasks involve long series of repetitive items that require substantial demands on vigilance and inhibition, particularly when reaching threshold levels. They are thus susceptible to distraction and vigilance factors – many times more so than reading or language tests. Furthermore, the reliability co-efficients for the sensory processing tasks do compare favourably to some more standardised instruments commonly used with children. For example, the Mazes and Picture Arrangement subtests from the WISC-III (Wechsler, 1992) have similar test-retest reliability co-efficients ($r = .61$ for Mazes and $r = .67$ for Picture Arrangement). Three subtests from a widely used measure of phonological awareness (Phonological Abilities Test; Muter, Hulme & Snowling, 1997) also have test-retest reliability co-efficients in the same range: Rhyme Production ($r = .5$); Phoneme Deletion – End Sounds ($r = .6$) Word Completion – Syllables ($r = .58$).

The test-retest reliability coefficients for psychometric measures listed above were obtained over a period of 12-63 days (WISC-III) and three weeks (Phonological Abilities Test). When similar tasks are re-tested over a longer period the reliability decreases. For example, the test-retest reliability of nine of WISC-R (Wechsler, 1974) subtests have a co-efficient of .62 or lower over a three year period (Truscott, Marrett &

Smith, 1994). The test-retest reliability of the CPM (Raven et al., 1995), which was used as a non-verbal measure of ability in this study, has been found to decrease from high levels ($r = .85 - .9$) over a period of weeks to only moderate levels ($r = .59$) over a six month period. Given the data used to estimate the test-retest reliability of the auditory and visual processing tasks in the present study was collected in two phases separated by a period of approximately nine months, one can consider the reliability of the tasks to be adequate.

5.4.4 *Between group analyses for auditory tasks*

5.4.4.1 *Catch trial performance*

The data from participants who made more than 25% errors on the catch trials were removed from all further analyses on the particular variable due to concerns about the effects of vigilance on thresholds. Table 7 summarises the catch trial performance of the dyslexic and control participants for the four auditory tasks at Phase 1 and Phase 4. The number of participants from each group who were removed from each analysis is shown. The percentage of errors made on catch trials for each of these participants is shown in brackets. After removal of these participants, a non-parametric Mann-Whitney U test was used to evaluate between group differences on catch trial performance. No significant between group differences were evident for any of the analyses: 2 Hz FM, $U = 1634$; $p = .159$ at Phase 1, $U = 1768$; $p = .438$ at Phase 4, 240 Hz FM, $U = 1806$; $p = .159$ at Phase 1 and $U = 1794$; $p = .417$ at Phase 4, 2 Hz AM, $U = 1703$; $p = .349$ at Phase 1, $U = 1749$; $p = .417$ at Phase 4, and 20 Hz AM, $U = 1663$; $p = .102$ at Phase 1, $U = 1794$; $p = .389$ at Phase 4.

Table 7.

Number of participants removed from analyses of psychoacoustic variables due to high catch trial errors. The number of participants from each group who were removed and their respective error rates on catch trials is shown.

	Control (<i>n</i> = 52)		Dyslexic (<i>n</i> = 70)	
	Phase 1	Phase 4	Phase 1	Phase 4
2 Hz FM	0	0	2 (34%, 58%)	2 (37.5%, 33%)
240 Hz FM	2 (33%, 28%)	1 (28%)	1 (28%)	1 (33%)
2 Hz AM	0	0	1 (50%)	2 (50%, 33%)
20 Hz AM	2 (33%, 35%)	0	2 (38%, 30%)	0

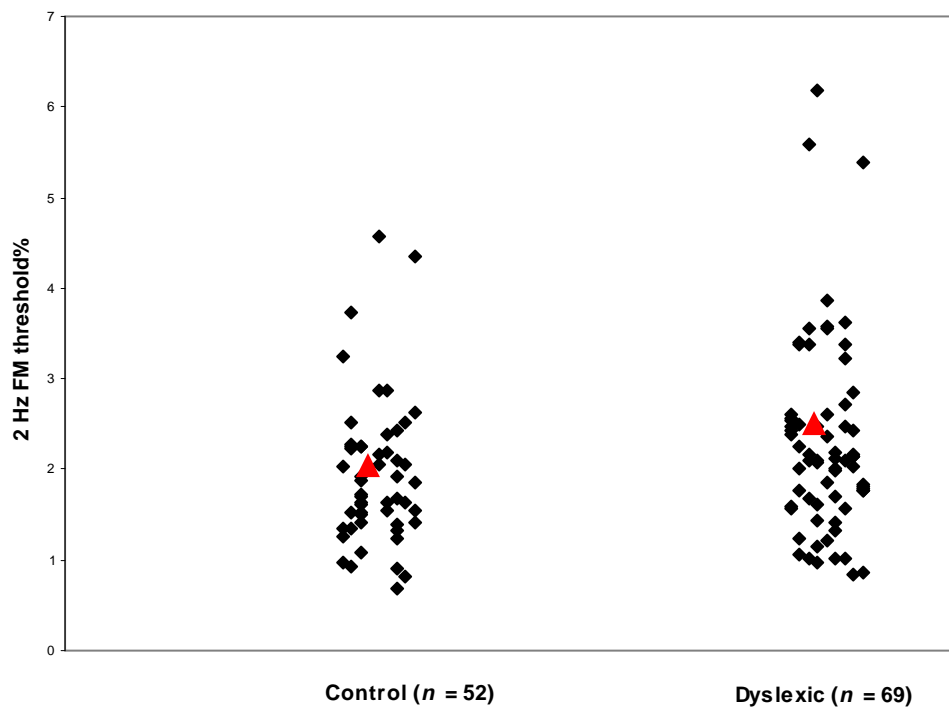
5.4.4.2 Auditory thresholds

Square root transformations were applied to all the distributions to stabilise the variances prior to analysis. All other assumptions of the t-test for independent groups were obeyed. The results of the analyses are presented in Table 8. The dyslexic group had significantly higher thresholds for 2 Hz FM, 240 Hz FM and 20 Hz AM at both Phase 1 and Phase 4, indicating that they were less sensitive than the control readers to these stimulus conditions. For the 2 Hz AM stimulus, the dyslexic group were significantly less sensitive than control readers at Phase 1. However, this effect was not replicated in Phase 4 where no significant between group differences were observed. The data for all of the auditory variables at both phases are presented graphically in Figures 6-13. The data from participants who were excluded from the between groups analyses because of low catch trial accuracy are not included in the figures.

Table 8.

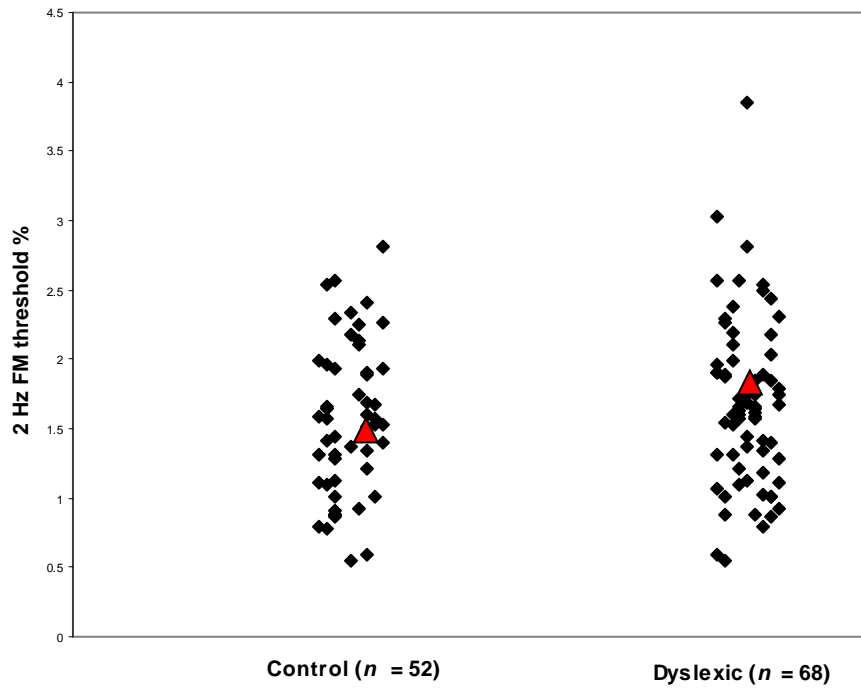
Results of independent groups t-test analyses on psychoacoustic variables at Phases 1 and 4.

	<i>df</i>	<i>t</i>	<i>p</i>	Cohen's <i>d</i>
2 Hz FM				
Phase 1	118	-1.95	.05	.28
Phase 4	118	-3.82	<.0005	.45
240 Hz FM				
Phase 1	117	-4.38	<.0005	.38
Phase 4	118	-2.66	.01	.30
2 Hz AM				
Phase 1	119	-4.4	<.0005	.55
Phase 4	118	-1.33	.184	.21
20 Hz AM				
Phase 1	116	-2.36	.019	.21
Phase 4	120	-1.96	.05	.25



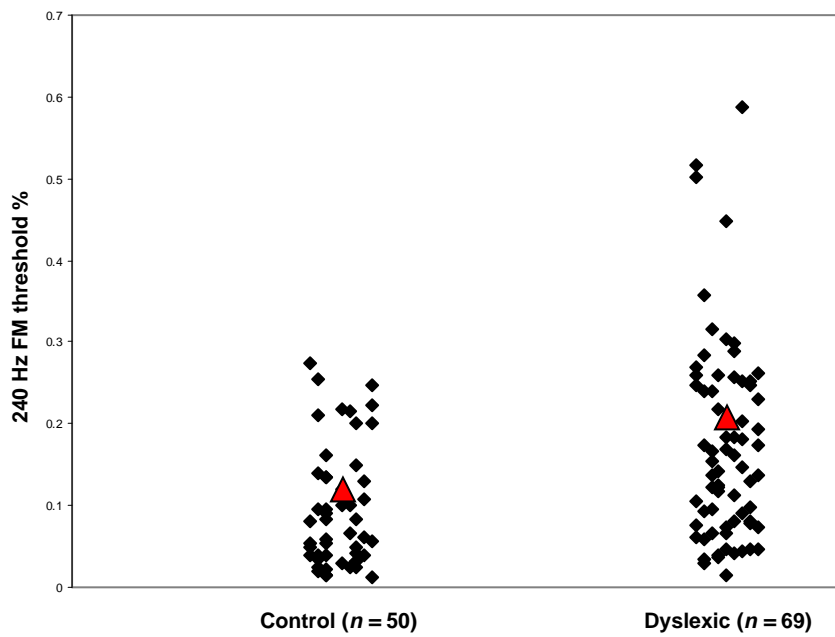
Note. \blacktriangle group mean.

Figure 6. Modulation detection thresholds for 2 Hz FM at Phase 1 (non-transformed data).



Note. \blacktriangle group mean.

Figure 7. Modulation detection thresholds for 2 Hz FM at Phase 4 (non-transformed data).



Note. \blacktriangle group mean.

Figure 8. Modulation detection thresholds for 240 Hz FM at Phase 1 (non-transformed data).

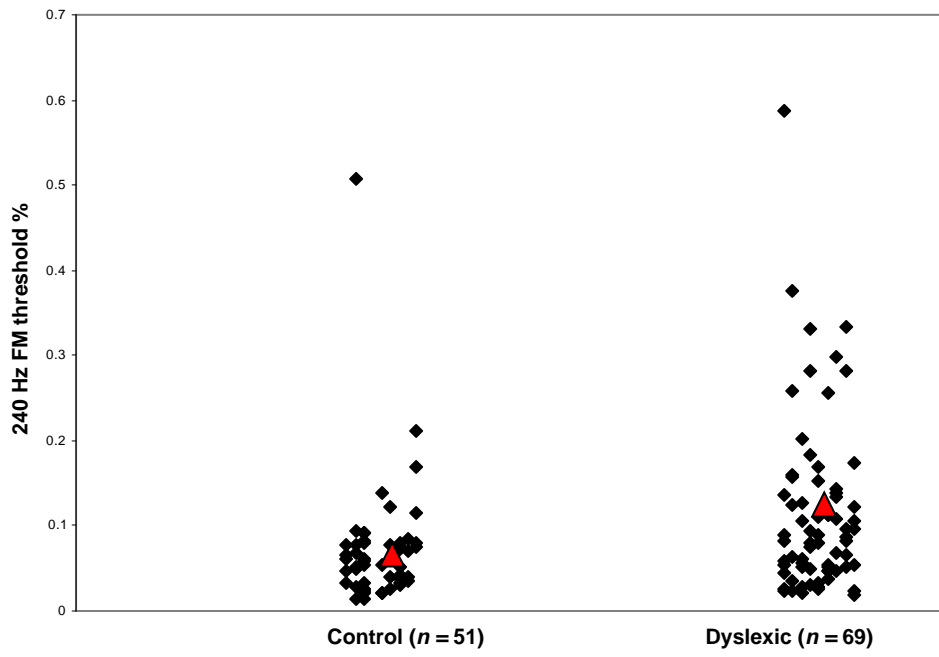


Figure 9. Modulation detection thresholds for 240 Hz FM at Phase 4 (non-transformed data). Note. \blacktriangle group mean.

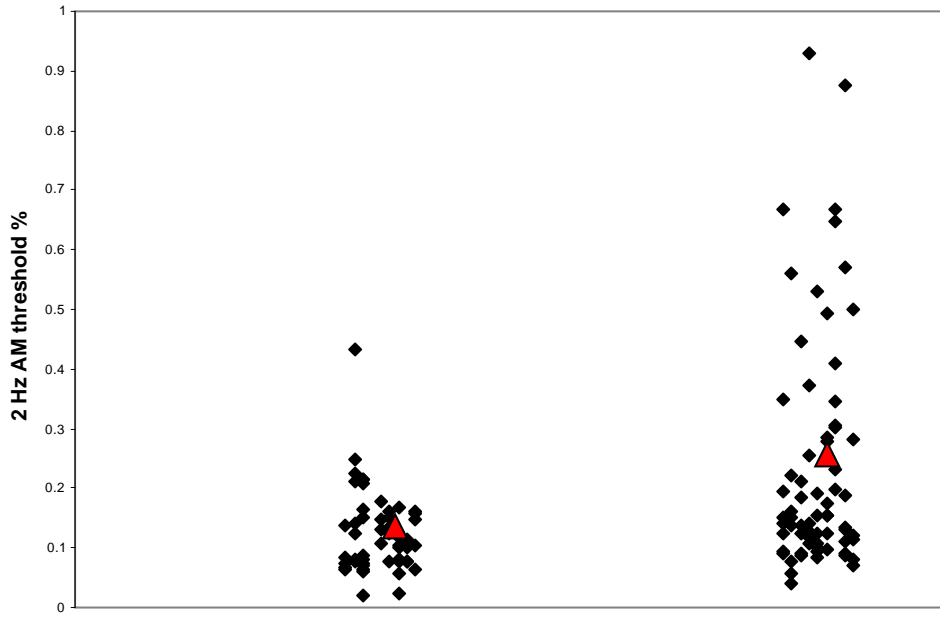


Figure 10. Modulation detection thresholds for 2 Hz AM at Phase 1 (non-transformed data). Note. \blacktriangle group mean.

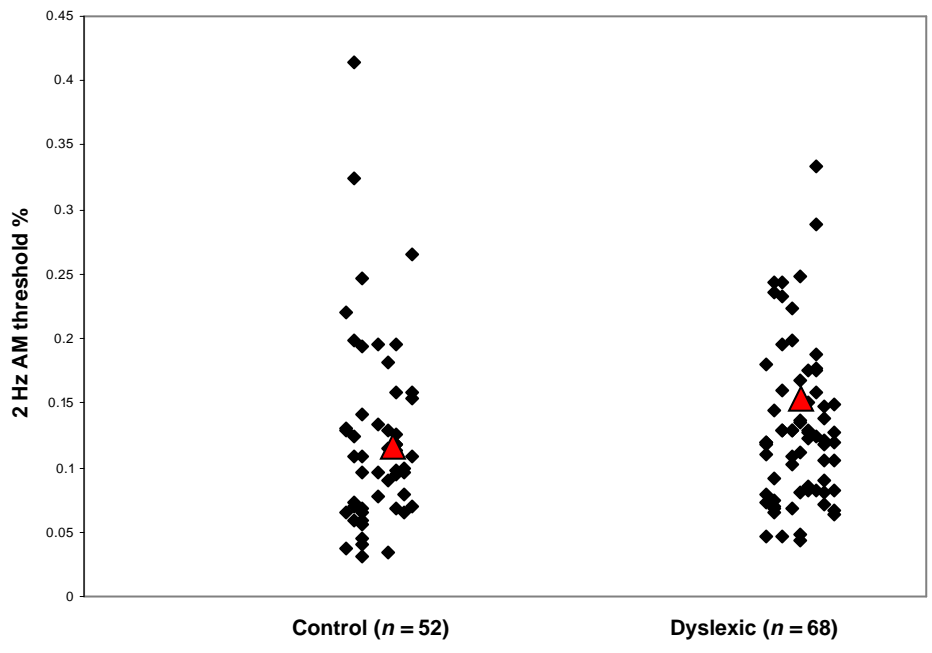


Figure 11. Modulation detection thresholds for 2 Hz AM at Phase 4 (non-transformed data). Note. =▲group mean.

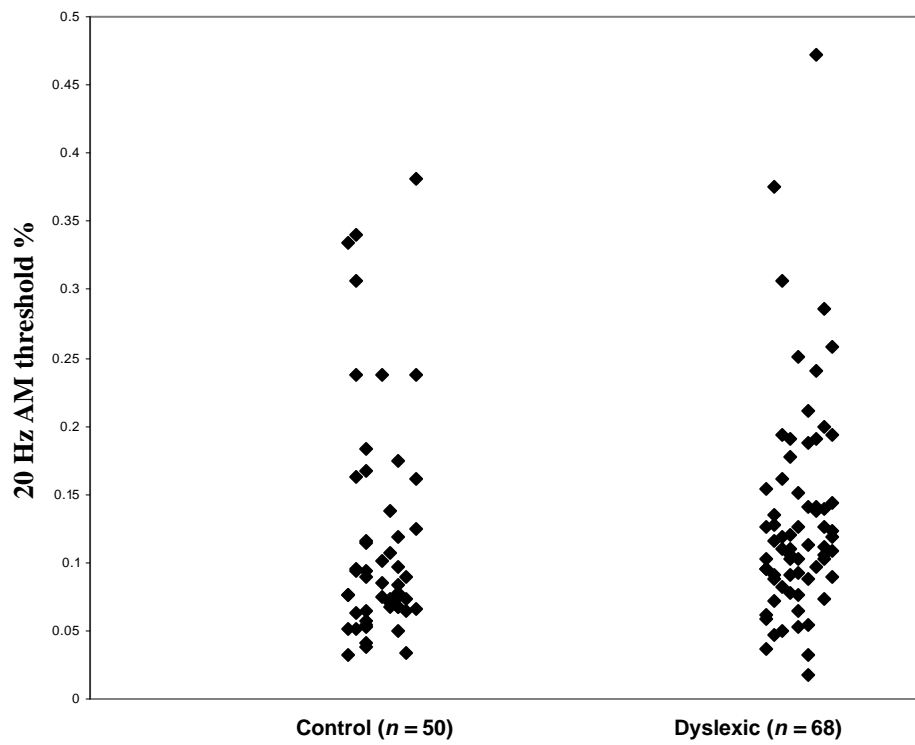


Figure 12. Modulation detection thresholds for 20 Hz AM at Phase 1 (non-transformed data). Note. =▲group mean.

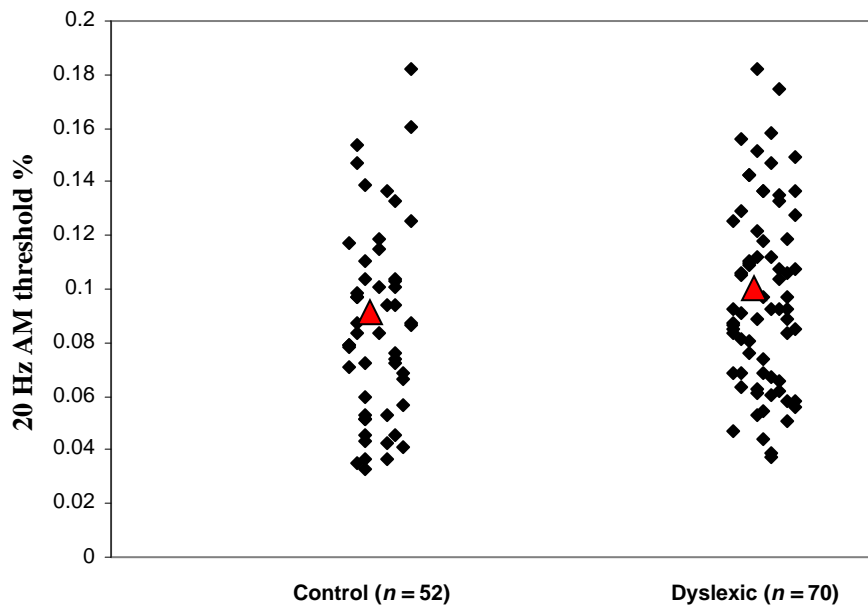


Figure 13. Modulation detection thresholds for 20 Hz AM at Phase 4 (non-transformed data). Note. \blacktriangle = group mean.

5.4.4.3 Discussion of auditory analyses

The internal replication of results in the same participants across time adds weight to the reliability of these results. The data also provide an external replication of studies showing dyslexic groups to be impaired across a range of acoustic tasks requiring processing of basic acoustic dimensions, such as frequency and amplitude

modulations (e.g., McAnally & Stein, 1997; Menell et al., 1999; Witton et al., 1998; Witton et al., 2002). However, the major prediction that the dyslexic group would show a specific temporal auditory impairment was not supported. In addition to being consistently less sensitive than the control group for the temporal stimuli 2 Hz FM and 20 Hz AM, the dyslexic group were also impaired in detection of the 240 Hz FM stimulus at both phases of the study. The 240 Hz FM stimulus modulates too rapidly to be tracked in time by temporal mechanisms in the auditory system. Instead, it is detected on the basis of spectral cues (Talcott et al., 1999). The auditory impairment found in this study in dyslexics is therefore more general in nature than the deficit previously described by Witton and colleagues (e.g., Witton et al., 1998; Witton et al., 2002).

The inconsistency across studies may result from the different levels of statistical power employed. For example, although Witton et al. (2002). did not find a statistically significant between groups effect for the non-temporal 240 Hz FM variable, their effect size for that stimulus was in the moderate to strong range (Cohen's $d = .59$). The current study had power of $\sim .89$ to find this size effect, while the Witton et al. study had low power ($\delta = .44$) to find this effect size. The inconsistent results between the studies can therefore be explained in terms of the statistical power of the individual studies. The results of the current study also demonstrate that care needs to be taken in using p values as the sole measure of the presence of an effect. That is, just because the p level infers non-significance does not mean that there is no meaningful effect (Ives, 2003; Schmidt & Hunter, 1995). Future studies should carefully evaluate measures of effect size and also take the statistical power of a study into account before drawing conclusions about the sensory processing characteristics of dyslexic groups.

In the case of the present study, although significant between group differences were observed, the effect sizes were in the small to moderate range (Cohen's $d = .21$ -

.55), indicating that substantial overlap existed between groups. Importantly however, the effect sizes were within similar ranges at both phases of the study. In general, the effect sizes for the group differences on the four auditory tasks were smaller than those reported by Witton et al. (2002). The smaller effect sizes in the current study may be due to problems associated with testing children rather than the adult population sampled by Witton et al. Children may be more prone to factors such as distractibility or inattention than adults; factors which can adversely affect psychophysical thresholds and add noise to the data. Witton et al. also conducted testing in a controlled laboratory environment. In contrast, the current study was conducted in a school setting, where complete control over the testing environment was more difficult to attain. Differences in testing conditions may therefore also have contributed to the smaller effect sizes found in the current study.

5.5 Between group analyses for coherent motion task

5.5.1 Catch trial performance

Participants who made greater than 25% errors on the catch trials for the coherent motion task were removed from all further analyses due to concerns about the impact of vigilance on motion detection thresholds. At Phase 1, one dyslexic participant was removed prior to the analysis due to concerns about vigilance (catch trial errors = 35%), while at Phase 4 none of the participants made more than 25% errors on the catch trials. A non-parametric Mann Whitney U test demonstrated that there were no significant between group differences for catch trial performance at Phase 1, $U = 1770$; $p = .568$, or Phase 4, $U = 1804$; $p = .78$.

5.5.2 *Motion sensitivity*

A square root transform was used to stabilise the variance in the distributions at both Phase 1 and Phase 4 before evaluating between group differences. All other assumptions of the analyses were met. At Phase 1, an independent groups t-test revealed that the dyslexic group was significantly less sensitive to coherent motion than the control group, $t(119) = -3.7; p < .0005$. This effect was replicated at Phase 4, $t(120) = -2.2; p = .023$. The motion detection performance of the dyslexic and control groups at Phase 1 and Phase 4, including individual data, is presented Figures 14 and 15.

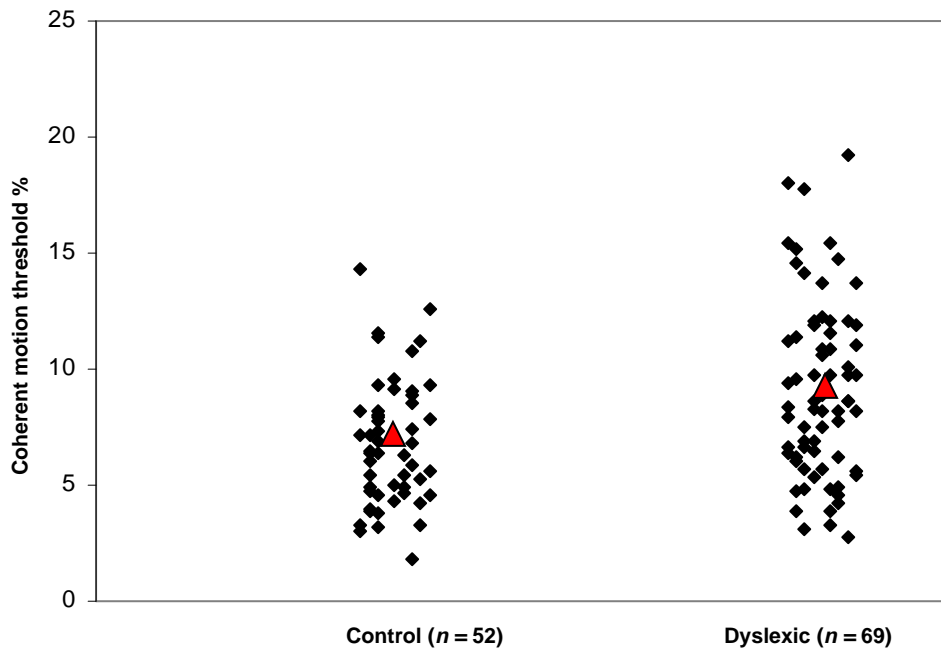


Figure 14. Coherent motion thresholds for control and dyslexic groups for Phase1
 Note. \blacktriangle group mean.
 (non-transformed data).

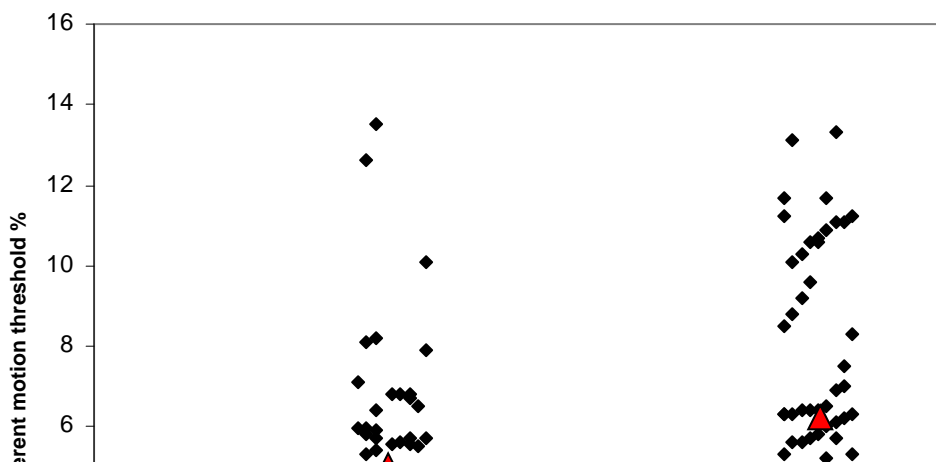


Figure 15. Coherent motion thresholds for control and dyslexic groups for Phase1 (non-transformed data). Note. \blacktriangle group mean.

5.5.3 Discussion of coherent motion analyses

These results provide an important external replication of previous research that has demonstrated impairments in motion sensitivity in dyslexic groups using the same coherent motion detection task (e.g., Conlon et al., 2004; Hansen et al., 2001; Talcott et al., 2003; Wilmer et al., 2004), thus demonstrating the reliability of the results. The reliability of findings of coherent motion deficits in the dyslexic group was further enhanced by the demonstration that the results could be replicated internally in the same participants across time. However, in the auditory section above, it was noted that in addition to measures of statistical significance, measures of effect size should be taken into account before drawing conclusions about the sensory processing characteristics of dyslexic groups. In the case of the present study, the effect sizes for these analyses were

in the moderate to strong range (Cohen's $d = .69$ at Phase 1 and Cohen's $d = .40$ at Phase 4). As was the case for the auditory data, these effects are smaller than have been found in the two previous studies using the same task from which effect sizes could be calculated. For example, Conlon et al. (2004) reported a strong effect size when comparing groups of dyslexic and control adults (Cohen's $d = 1.22$), as did Wilmer et al. (2004; Cohen's $d = .90$). The smaller effects found in the current study may be associated with the difficulties in testing children in a school setting discussed in the auditory section above.

The motion detection results of the current investigation stand in contrast to those of Kronbichler et al. (2002) who found that no significant impairments in German dyslexic children on the same motion coherence task (Cohen's $d = .04$). The results of a recent study may shed light on this inconsistency. Wilmer et al. (2004) demonstrated that a deficit in detecting coherent motion was associated with low accuracy on reading skills tests, while a deficit in speed discrimination was associated with speed of responding on these same tests. The children in the dyslexic group in the current study were selected on the basis of low accuracy scores on reading tests. In contrast, the German children in the Kronbichler et al. (2002) study were selected on the basis of low reading and spelling fluency. Thus, Kronbichler et al. may have sampled a dyslexic sub-group, whose cognitive and neurological deficits are defined by a deficit in rate of processing.

5.6 Summary of Between Group Analyses for Auditory and Coherent Motion Tasks

The results of the current study demonstrated that the dyslexic group had a general auditory processing impairment, rather than an impairment specific to temporal stimuli. Replicating this effect internally over time provides some evidence for the

reliability of the results. However, the effect sizes for the auditory analyses were in the small to moderate range. On the basis of Cohen's (1988) conventions it would be tempting to describe these effects as trivial and to suggest that the significant between group differences were an artefact of the statistical power of the present study. In contrast, the magnitude of the effect for the coherent motion task was stronger and would typically be described as meaningful and to have practical significance. However, effect sizes, such as Cohen's d , are only measures of the average effect between groups. For example, a Cohen's d of .28 for the 2 Hz FM stimulus indicates only that, on average the dyslexic group's thresholds were .28 of a standard deviation unit higher than the mean of the control group. Therefore, while effect sizes are useful in describing the magnitude of the average effect, they are not descriptive of individual performances and should never be used on their own as a benchmark for meaningfulness (Cohen, 1992). Visual inspection of the individual data (see Figures 6-13) for the auditory tasks demonstrates that, despite the small effect sizes, there was a sub-group of participants who had poor acoustic sensitivity relative to the control group. For the coherent motion data, the opposite applied. That is, despite the larger effect sizes found for this stimulus, there was still substantial overlap between the thresholds of the two groups. For this reason further data exploration on the individual performance of participants was undertaken.

This study was particularly interested in determining the number of dyslexic individuals who had sensory deficits relative to the control group mean, and if these deficits were stable over time. To do this it was necessary to adopt criteria to define deviant performance. In neuropsychological and clinical research it is common to compare the performance of an individual to the performance of a normative sample to determine deviant performance. For the purposes of the current study, no normative data was available on the psychophysical tasks used to assess sensory sensitivity.

Instead, the procedure of Ramus et al. (2003) was followed, in which a threshold was set at 1.65 SD standard deviations from the control group mean. This corresponds to the 95% confidence interval (one-tailed) of that group. Ramus et al have referred to this approach as a deviance analysis. Following Ramus et al., deviance criteria was applied in three steps: (a) standardise the distributions, (b) compute the control group mean and identify control participants who qualify for deviant performance, and (c) recompute the control mean and standard deviation with these control participants removed and identify dyslexic participants who have a threshold 1.65 SD or greater above the control mean. This method avoids the potential impact of anomalous thresholds in the control group when computing the control group mean. Deviance analyses were conducted on the thresholds for 2 Hz FM, 240 Hz FM and coherent motion. The 2 Hz FM stimulus was chosen because of its widespread use in the literature. The 240 Hz FM stimulus was chosen as a control variable of non-temporal processing.

5.7 Deviance Analysis

Phase 1

For 2 Hz FM, 20% (14) of participants from the dyslexic group had deviant thresholds and 11% (6) of the control group also had deviant thresholds. For 240 Hz FM, 42% (29) of the dyslexic participants had deviant thresholds. Seventeen percent (9) of the control group also had deviant thresholds at Phase 1 for 240 Hz FM. In the dyslexic group, 14.6% (10) of the sample had a deviant threshold for the coherent motion stimulus, while 7.6% (4) of the control group also had a deviant threshold for coherent motion. The non-transformed distributions for the individual participants in the dyslexic and control groups for the 2 Hz FM, 240 Hz FM and coherent motion variables are shown in Figures 16-18. The dotted line in the figures represents the cut-off point for deviance.

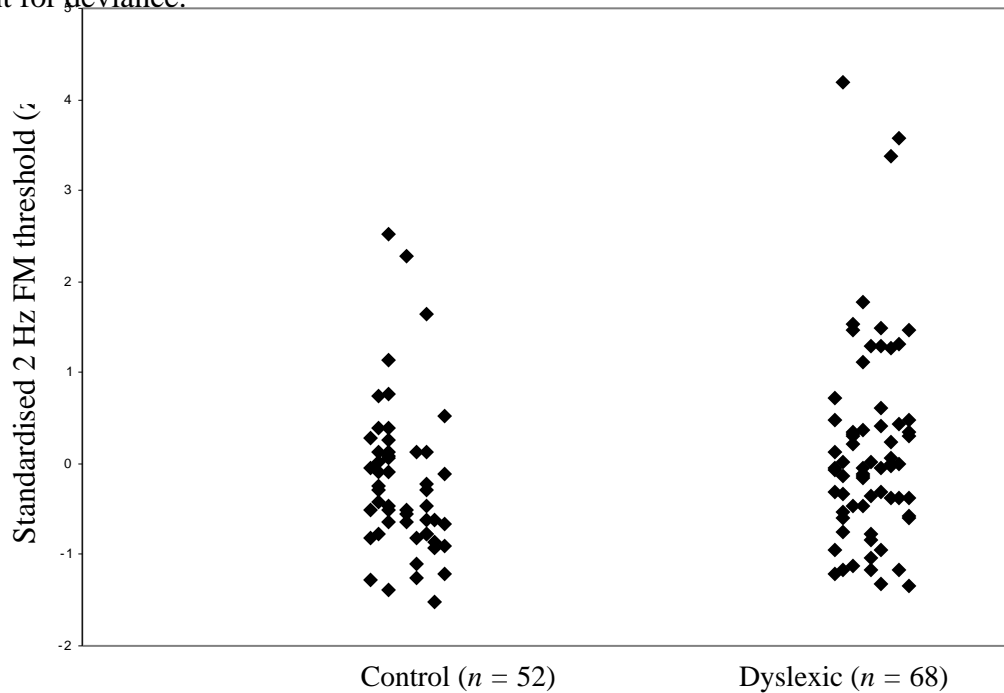


Figure 16. Modulation detection thresholds for 2 Hz FM at Phase 1. These are standardised distributions prior to removal of anomalous control scores. The dotted line in the figures represents the cut-off point for deviance and all points above the dotted line represent deviant performance.



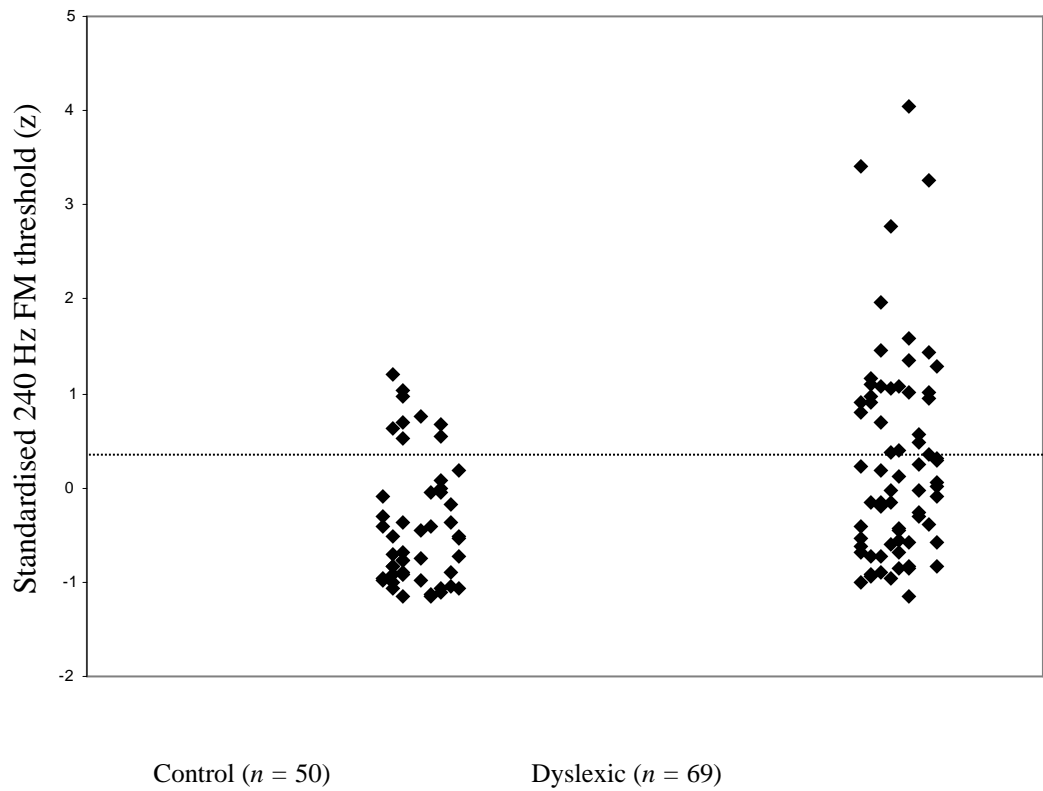


Figure 17. Modulation detection thresholds for 240 Hz FM at Phase 1. These are standardised distributions prior to removal of anomalous control scores. The dotted line in the figures represents the cut-off point for deviance and all points above the dotted line represent deviant performance.

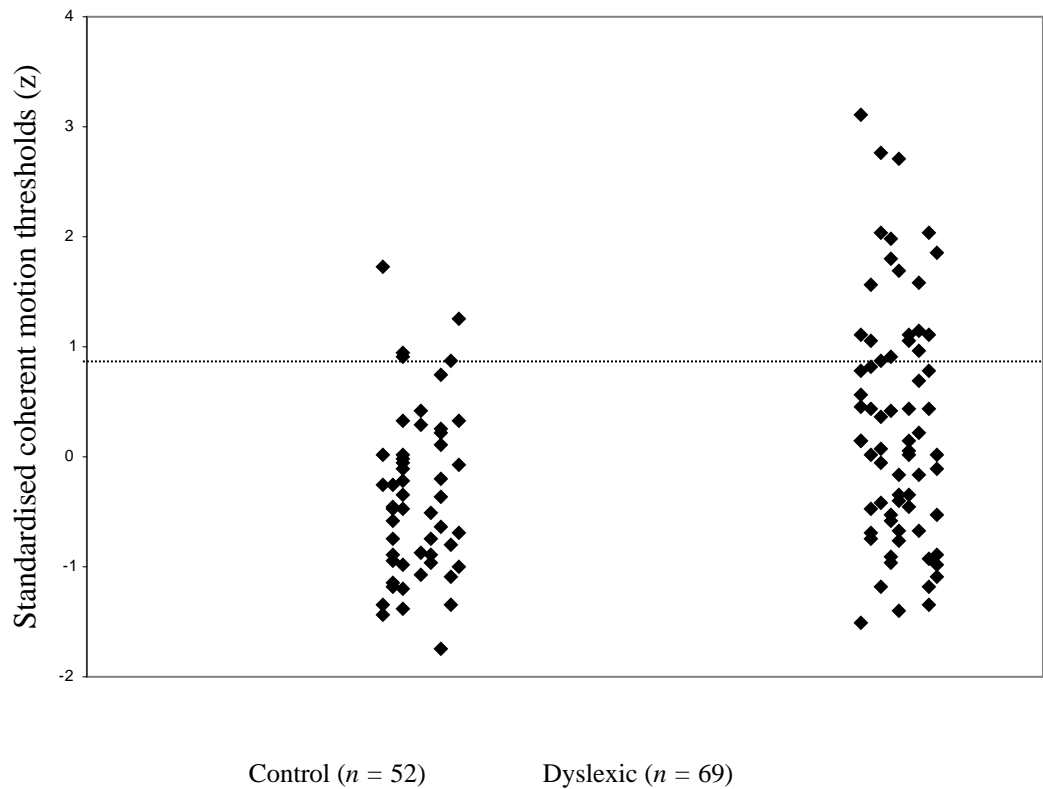


Figure 18. Coherent motion thresholds for control and dyslexic groups for Phase1. These are standardised distributions prior to removal of anomalous control scores. The dotted line in the figures represents the cut-off point for deviance and all points above the dotted line represent deviant performance.

Phase 4

A similar proportion of each group had deviant thresholds. For 2 Hz FM, 24% (17) of the dyslexic group and 9.6% (5) of the control group had deviant thresholds. For 240 Hz FM, 28% (20) of the dyslexic group and 9.6% (5) of the control group were classified as having deviant thresholds. For coherent motion, 25% (17) of the dyslexic group and 11.5% (6) of the control group showed deviant performance. The non-transformed distributions for the individual participants in the dyslexic and control groups for the 2 Hz FM, 240 Hz FM and coherent motion variables are shown in Figures 19-21 with the dotted line representing the cut-off point for deviance.

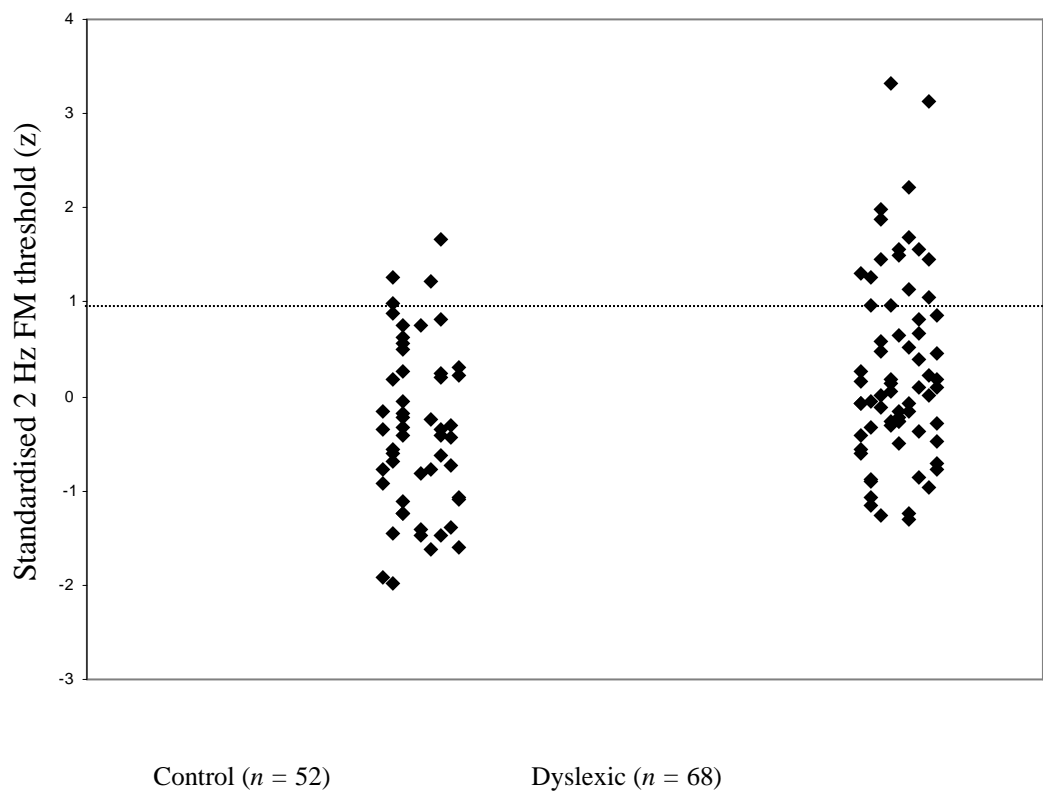


Figure 19. Modulation detection thresholds for 2 Hz FM at Phase 4. These are standardised distributions prior to removal of anomalous control scores. The dotted line in the figures represents the cut-off point for deviance and all points above the dotted line represent deviant performance.

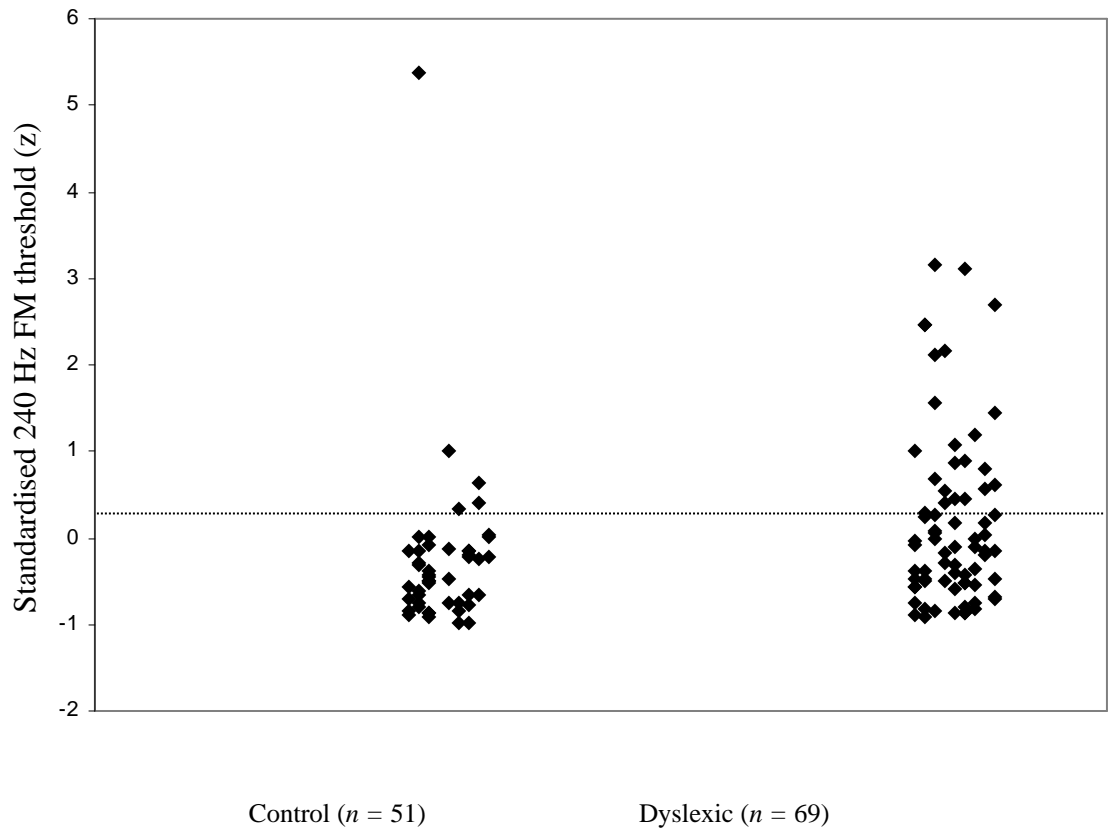


Figure 20. Modulation detection thresholds for 240 Hz FM at Phase 4. These are standardised distributions prior to removal of anomalous control scores. The dotted line in the figures represents the cut-off point for deviance and all points above the dotted line represent deviant performance.

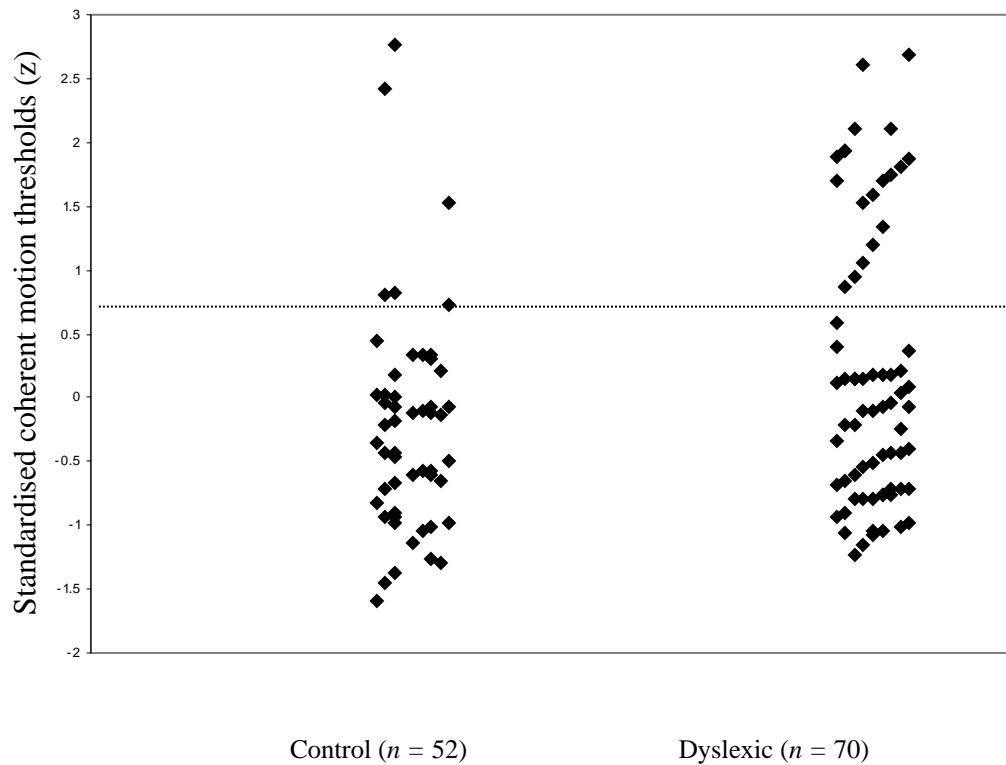


Figure 21. Coherent motion thresholds for control and dyslexic groups for Phase 4. These are standardised distributions prior to removal of anomalous control scores. The dotted line in the figures represents the cut-off point for deviance and all points above the dotted line represent deviant performance.

Stability of performance across time

Stability of performance across time was evaluated by determining if participants who had deviant thresholds at Phase 1 also had deviant thresholds at Phase 4. To investigate this issue, the deviance classification of each participant at Phase 1 and Phase 4 was compared. Only 4 dyslexic participants (4% of the sample) and 1 control participant (2% of the sample) had deviant thresholds for 2 Hz FM. Twenty (27% of the sample) dyslexic participants and 9 control participants (17% of the sample) had inconsistent thresholds across both phases. For 240 Hz FM, 13 dyslexic

participants (18% of the sample) and 2 controls (4% of the sample) had deviant thresholds across both phases. Inconsistent performance was found in 23 (32% of the sample) dyslexic participants and 9 (17% of the sample) control participants. For coherent motion, 12 dyslexic participants (17% of the sample) and 2 controls (4% of the sample) were consistently deviant. Fourteen (19%) dyslexic participants and 6 (11%) control participants also had inconsistent thresholds. The number of control and dyslexic participants who had deviant thresholds for coherent motion, 2 Hz FM and 240 Hz FM across both phases of the study is presented in Table 9.

Table 9.

Number of control and dyslexic participants who had deviant thresholds for coherent motion, 2 Hz FM and 240 Hz FM across both phases.

	Number of deviant thresholds	
	Control	Dyslexic
Coherent motion	2 (4%)	12 (17%)
2 Hz FM	1 (2%)	4 (5%)
240 Hz FM	2 (4%)	13 (18%)

Summary and discussion of deviance analysis

The data from the deviance analyses demonstrated that stable sensory impairments existed only in a small sub-group of children. Deviant thresholds at both phases for 2 Hz FM were found in 5% of the dyslexic group, while for the 240 Hz FM stimulus, deviant thresholds were found in 18% of the dyslexic sample. It seems that in general, a greater proportion of the dyslexic group had more difficulty for the 240 Hz FM stimulus, which is the opposite of what the auditory temporal processing hypothesis would predict (e.g., Witton et al., 2002). There were also a limited number of control participants who had deviant thresholds for these acoustic stimuli (2% for 2 Hz FM and 4% for 240 Hz FM). In a similar manner to the auditory data, the results of the deviance

analysis for the coherent motion task indicated only 17% of the dyslexic sample had deviant thresholds across both phases. A small number of the control group (4%) were also found to have deviant motion detection performance.

Finding that sensory processing impairments exist in individual participants rather than being a universal characteristic of dyslexic groups is consistent with previous research that has considered individual data. The incidence of deviant sensory thresholds observed in the current study was comparable to previous studies (e.g., Edwards et al., 2002; Ramus et al., 2003; Witton et al., 1998) when the two phases were examined separately. For example, Edwards et al. (2004) reported 33% of their dyslexic sample had motion detection impairments. In the auditory domain, data presented by Witton et al. (1998), indicated a similar number of dyslexics (38% of the sample) had thresholds for 2 Hz FM higher than the highest threshold in the control group. However, when both phases are considered together, the incidence of sensory processing impairments observed in the present study was much lower than in these previous investigations. The relatively lower incidence of sensory impairment in the current study may have been due to the strict criteria employed. Participants were classified as having a sensory impairment if they had deviant thresholds relative to the control group mean at both phases of the study. Children who had inconsistent thresholds (i.e., normal at one time and abnormal at another) were not considered to have stable sensory impairments. Other studies (e.g., Edwards et al., 2004; Ramus et al., 2003) have used one measure of sensory processing to determine abnormal thresholds.

These data therefore demonstrate that the criteria employed to assess deviance can affect the relative incidence reported by a particular study. Employing only one estimate of a sensory threshold could lead to overestimation of the incidence of sensory impairments in both dyslexic and control groups. These data also demonstrate a

substantial portion of both the dyslexic and control groups performed inconsistently on the sensory processing measures across Phase 1 and Phase 4. That is, they showed normal sensory sensitivity at one phase and abnormally poor sensitivity at the other phase. It was no more common for thresholds for any task to be deviant at Phase 1 and normal at Phase 4, than it was for the reverse to occur so the inconsistent results cannot be attributed simply to practice effects due to greater familiarity with the tasks. Limited support for inconsistent responding on sensory processing tasks has come from Kronbichler et al. (2002) who reported one dyslexic participant who had an extremely high (50%) threshold on one threshold measurement of motion detection and performed well (7%) on a second threshold run within the same testing session. The impact of the way that threshold estimates were measured had on the consistency of responding and the test-retest reliability of the sensory processing tasks will be discussed in detail in the General Discussion.

In summary, the majority of the dyslexic sample had reading difficulties without any sensory processing deficit, indicating a sensory deficit is not necessary to cause dyslexia. Nor is a sensory deficit sufficient to cause dyslexia, as a number of control participants were observed to have abnormal thresholds. Nevertheless, these results do not preclude sensory processing making a contribution to reading difficulties in some children. Indeed, if sensory processing and reading ability both exist on a continuum as has been previously suggested (Demb, Boynton, Best et al., 1998; Shaywitz et al., 1992; Stanovich & Siegel, 1994), correlation and regression analyses may shed further light on the relationship rather than analyses which examine differences between defined reader groups. The relationships between the summary reading variables and sensory processing measures were investigated in the following analyses.

5.8 Relationships Between Sensory Processing and Reading Measures

5.8.1 Correlations between psychophysical, cognitive and reading measures

Low to moderate correlations ($r = .25 - .46$) existed between thresholds for the psychoacoustic variables coherent motion and the summary reading variables ORTHOGRAPHY, PHONOLOGY AND READING at Phase 1. These data replicate previous studies that have reported significant relationships between these variables (Talcott et al., 1999; Talcott, Witton et al., 2000; Talcott et al., 2002; Witton et al., 1998; Witton et al., 2002;). In addition to external replication of previous research, the current study replicated the results internally by demonstrating that similar small to moderate relationships could be found at retesting nine months later ($r = .29 - .42$). Across both phases of the study coherent motion thresholds showed small, yet statistically significant correlations to thresholds obtained for the 2 Hz FM stimulus. Thresholds for 240 Hz FM, however, were not related to coherent motion thresholds at either phase of the study. The two auditory thresholds were also significantly related at both phases. Significant correlations were also observed between thresholds for the three sensory processing tasks and the summary reading measures.

Table 10.

Correlations (Pearson's r) between auditory and visual processing measures and summary variables of PHONOLOGY, ORTHOGRAPHY and READING for dyslexic and control children at Phase 1 (N = 122).

	1	2	3	4	5	6	7
READING							
PHONOLOGY	.86**						
ORTHOGRAPHY	.86**	.59**					
IQ	.386**	.309**	.32**				
Coherent motion	-.46**	-.41**	-.32**	-.37**			
2 Hz FM	-.38**	-.31**	-.089	-.37**	-.24**		
240 Hz FM	-.25**	-.36**	-.236**	-.11	.17	.21*	

** P < .01 * P < .05

Table 11.

Correlations (Pearson's r) between auditory and visual processing measures and summary variables of PHONOLOGY, ORTHOGRAPHY and READING for dyslexic and control children at Phase 4 (N = 122).

	1	2	3	4	5	6	7
READING							
PHONOLOGY	.81**						
ORTHOGRAPHY	.85**	.5**					
IQ	.378**	.224*	.369**				
Coherent motion	-.42**	-.35**	-.178	-.39**			
2 Hz FM	-.39**	-.31**	-.248**	-.3**	.18*		
240 Hz FM	-.39**	-.33**	-.324**	-.26**	.12	.27**	

** P < .01 * P < .05

5.8.2 Regression analyses

Six separate hierarchical multiple regression analyses were performed – three using Phase 1 data and three using Phase 4 data. IQ score was always entered at Step 1 of the analyses. To account for individual differences in vigilance, the catch trial data for the three sensory processing tasks was always entered at Step 2 before the thresholds

for coherent motion, 2 Hz FM and 240 Hz FM were entered in a hierarchical manner at Step 3. All of the assumptions of these analyses were met.

5.8.2.1 ORTHOGRAPHY Phase 1

At Step 1 IQ accounted for 10.4% of the variance in ORTHOGRAPHY, $F(1,114) = 13.09$; $p < .0005$. At Step 2, participant vigilance did not account for additional variance, $F(3,111) = .485$; $p = .693$. At Step 3, sensory processing thresholds could account for an additional 13.9% of the variance in ORTHOGRAPHY, $F(3,108) = 6.65$; $p < .0005$. Both coherent motion thresholds (7%) and 240 Hz FM thresholds (3.7%) accounted for a significant unique portion of the variance in ORTHOGRAPHY.

Selected results from this analysis are presented in Table 12.

Table 12.

Regression analysis predicting participant's orthographic coding skill at Phase 1 (n = 115).

Step variable	R	R ²	Adjusted R ²	R ² change	Semi Partial R	β	p
Step 1							
IQ	.32	.104	.096				<.0005
Step 2							
Catch trials	-.34	.116	.083	.012			.693
1. Coherent motion					-.023	-.024	.796
2. 2 Hz FM					.078	.102	.278
3. 240 Hz FM					.023	.024	.798
Step 3							
Auditory & Visual thresholds	.505	.255	.206	.139			<.0005
1. Coherent motion					-.268	-.291	.002
2. 2 Hz FM					-.062	-.067	.46
3. 240 Hz FM					-.193	-.212	.022

5.8.2.2 ORTHOGRAPHY Phase 4

At Step 1 IQ accounted for 13.2% of the variance in ORTHOGRAPHY, $F(1,112) = 17.7$; $p < .0005$. At Step 2, participant vigilance did not account for additional variance, $F(3,109) = 1.64$; $p = .19$. At Step 3, sensory processing thresholds could account for an additional 16.3% of the variance in ORTHOGRAPHY, $F(3,106) = 8.99$; $p < .0005$. Coherent motion thresholds (13%) and sensitivity to 2 Hz FM (2.1%) each accounted for a significant unique portion of the variance in ORTHOGRAPHY.

Selected results from this analysis are presented in Table 13.

Table 13.

Regression analysis predicting participant's orthographic coding skill at Phase 4 (n = 115).

Step variable	R	R ²	Adjusted R ²	R ² change	Semi Partial R	β	p
Step 1							
IQ	.363	.132	.124				<.0005
Step 2							
Catch trials	.409	.167	.138	.035			.19
1. Coherent motion					.126	.126	.14
2. 2 Hz FM					-.08	-.08	.35
3. 240 Hz FM					.135	.15	.11
Step 3							
Auditory & Visual thresholds	.574	.33	.288	.163			.001
1. Coherent motion					-.363	-.391	<.0005
2. 2 Hz FM					-.148	-.154	.05
3. 240 Hz FM					.056	.06	.47

5.8.2.3 PHONOLOGY Phase 1

At Step 1 IQ accounted for 10% of the variance in PHONOLOGY, $F(1,114) = 12.55$; $p = .001$. At Step 2, participant vigilance did not account for additional variance,

$F(3,111) = .76; p = .515$. At Step 3, sensory processing thresholds could account for an additional 18.8% of the variance in PHONOLOGY, $F(3,108) = 9.65; p < .0005$.

Coherent motion thresholds (5.7%) and thresholds for 2 Hz FM (6.9%) accounted for a significant unique portion of the variance in PHONOLOGY. Selected results from this analysis are presented in Table 14.

Table 14.

Regression analysis predicting participant's phonological processing skill at Phase 1 (n = 115).

Step variable	R	R ²	Adjusted R ²	R ² change	Semi Partial R	β	p
Step 1							
IQ	.316	.10	.092				.001
Step 2							
Catch trials	.34	.118	.086	.018			.573
1. Coherent motion					.069	.07	.44
2. 2 Hz FM					.109	.113	.266
3. 240 Hz FM					-.049	-.05	.507
Step 3							
Auditory & Visual thresholds	.553	.306	.261	.188			<.0005
1. Coherent motion					-.24	-.261	.004
2. 2 Hz FM					-.264	-.285	.001
3. 240 Hz FM					-.136	-.149	.094

5.8.2.4 PHONOLOGY Phase 4

At Step 1 IQ accounted for 4.9% of the variance in PHONOLOGY, $F(1,112) = 5.98; p = .016$. At Step 2, participant vigilance did not account for additional variance, $F(3,109) = 2.16; p = .097$. At Step 3, sensory processing thresholds could account for an additional 17.7% of the variance in PHONOLOGY, $F(3,106) = 9.0; p < .0005$. Both coherent motion thresholds (8.7%) and sensitivity to 2 Hz FM (5%) accounted for a

significant unique portion of the variance in PHONOLOGY. Sensitivity to 240 Hz FM did not account for additional variance after accounting for IQ and vigilance and variance shared with 2 Hz FM and coherent motion. Selected results from this analysis are presented in Table 15.

Table 15.

Regression analysis predicting participant's phonological processing skill at Phase 4 (n = 115).

Step variable	R	R ²	Adjusted R ²	R ² change	Semi Partial R	β	p
Step 1							
IQ	.221	.049	.041				.016
Step 2							
Catch trials	.316	.10	.068	.051			.097
1. Coherent motion					.116	.117	.194
2. 2 Hz FM					-.123	-.135	.17
3. 240 Hz FM					.185	.205	.039
Step 3							
Auditory & Visual thresholds	.526	.276	.231	.177			<.0005
1. Coherent motion					-.295	-.318	<.0005
2. 2 Hz FM					-.224	-.232	.007
3. 240 Hz FM					-.079	-.085	.332

5.8.2.5 READING Phase 1

At Step 1 IQ accounted for 15.5% of the variance in READING, $F(1,114) = 20.66$; $p < .0005$. At Step 2, participant vigilance did not account for additional variance, $F(3,111) = .814$; $p = .489$. At Step 3, sensory processing thresholds could account for an additional 16.6% of the variance in READING, $F(3,108) = 8.99$; $p < .0005$. Coherent motion thresholds (8.2%) and 240 Hz FM thresholds (3.1%) accounted for significant unique portions of the variance in READING. Sensitivity to 2 Hz FM accounted for an additional 1.7% of unique variance, however this effect was not

statistically significant ($p = .09$). Selected results from this analysis are presented in Table 16.

Table 16.

Regression analysis predicting participant's overall reading skill at Phase 1 (n = 115).

Step variable	R	R ²	Adjusted R ²	R ² change	Semi Partial R	β	p
Step 1							
IQ	.393	.155	.147				<.0005
Step 2							
Catch trials	.416	.173	.143	.018			.489
1. Coherent motion					.018	.018	.838
2. 2 Hz FM					.131	.136	.133
3. 240 Hz FM					-.016	-.017	.853
Step 3							
Auditory & Visual thresholds	.583	.339	.296	.166			<.0005
1. Coherent motion					-.287	-.312	<.0005
2. 2 Hz FM					-.131	-.141	.09
3. 240 Hz FM					-.177	-.194	.026

5.8.2.6 READING Phase 4

At Step 1 IQ accounted for 14% of the variance in READING, $F(1,112) = 19.03$; $p < .0005$. At Step 2, participant vigilance did not account for additional variance, $F(3,109) = .307$; $p = .108$. At Step 3, sensory processing thresholds could account for an additional 21.2% of the variance in READING, $F(3,106) = 13.01$; $p < .0005$. Coherent motion thresholds (9.9%) and sensitivity to 2 Hz FM (5.2%) accounted for a significant unique portion of the variance in READING. Sensitivity to 240 Hz FM did not account for additional variance after accounting for IQ and vigilance. Selected results from this analysis are presented in Table 17.

Table 17.

Regression analysis predicting participant's overall reading skill at Phase 4 (n = 115).

Step variable	R	R ²	Adjusted R ²	R ² change	Semi Partial R	β	p
Step 1							
IQ	.374	.14	.133				<.0005
Step 2							
Catch trials	.429	.184	.156	.044			.108
1. Coherent motion					.07	.07	.408
2. 2 Hz FM					-.133	-.146	.118
3. 240 Hz FM					.188	.208	.028
Step 3							
Auditory & Visual thresholds	.63	.397	.359	.212			<.0005
1. Coherent motion					-.316	-.389	<.0005
2. 2 Hz FM					-.229	-.237	.002
3. 240 Hz FM					-.025	-.027	.73

5.8.3 Discussion of regression analyses

Thresholds for the temporal measures 2 Hz FM and coherent motion could account for small, but significant unique portions of the variance in phonological processing skill, orthographic coding ability and an overall measure of reading ability at both phases of this study. Thresholds for 2 Hz FM accounted for 1.7% and 5.2% of the variance in READING at Phase 1 and Phase 4 respectively. Coherent motion thresholds could account for 8.2% and 9.9% of the variance in the same measure. These data provide an external replication of previous research, which reported temporal auditory (4%) and motion (3%) sensitivity were significantly related to a component measure of overall word reading and spelling ability (Talcott et al., 2002). The results are also consistent with the finding of a significant association between coherent motion thresholds and overall word reading skill (Conlon et al., 2004).

The auditory temporal measure 2 Hz FM also accounted for significant unique portions of the variance in PHONOLOGY at both phases of the study (6.9% and 5%),

as did thresholds for coherent motion (5.7% and 8.7%). The amount of variance accounted for by these measures was less than the 34% reported by Witton et al. (2002) in adults; however, it was consistent with the results of a study which used a larger, unselected sample of children (Talcott et al., 2002). Talcott et al. also reported phonological skill was related to both auditory and visual processing. Auditory frequency discrimination ability accounted for 4% of the variance in a phonological measure and coherent motion thresholds could account for 3% in the same measure after accounting for vigilance and IQ. By providing an external replication of these results, the current study has demonstrated the reliability of these small, but significant relationships between phonological skill and auditory and visual processing. Importantly, the results were also replicated internally, thus providing additional evidence for the reliability of the results.

Thresholds for coherent motion accounted for the most unique variance in orthographic skills. It accounted for 7% and 13% of the variance in ORTHOGRAPHY at Phase 1 and Phase 4 respectively. However, the auditory variables 240 Hz FM was also related to orthographic skill at Phase 1, as were thresholds for 2 Hz FM at Phase 4. These findings are in contrast to those of Talcott, Witton et al. (2000) who found that a significant independent relationship existed between motion thresholds and orthographic coding ability after accounting for IQ. However, they are consistent with the results of a later study that demonstrated orthographic skill was related to both visual and auditory processing (Talcott et al., 2002). That motion thresholds also accounted for unique variance in phonological processing skill and overall reading skills also argues against an independent relationship between motion processing and orthographic coding. Similar relationships between coherent motion sensitivity and phonological and word reading skills have also been reported by other investigations (Conlon et al., 2004; Huslander et al., 2004; Talcott et al., 2002; Witton et al., 1998).

Therefore, the current study provided less evidence for a specific relationship between visual and orthographic processing, and between auditory and phonological processing, than some previous studies (e.g., Talcott, Witton et al., 2000). Nevertheless, the current data replicated previous findings that visual and auditory processing sensitivity covaries with orthographic and phonological processing skill.

Although in general the results of the present study replicated previous findings of significant relationships between temporal auditory and visual measures and reading skills, there was one major inconsistency that requires explanation. That is, the non-temporal variable 240 Hz FM accounted for significant unique variance in READING at Phase 1 (3.1%) and in ORTHOGRAPHY at Phase 1 (3.7%). The relationship observed between READING and 240 Hz FM may be mediated by ORTHOGRAPHY (which is a component of the summary READING variable). Given that certain reading skills are related to this control variable, it might be concluded that the relationship observed are the result of cognitive demands common to the sensory processing and reading measures. Two factors do not support this proposal. Firstly, 240 Hz FM was not related to PHONOLOGY. There is no reason to suspect that the phonological tasks placed less demands on cognitive resources such as attention or memory than the orthographic tasks. Secondly, the relationship between 240 Hz FM and orthographic coding was not observed at Phase 4; nor has it been found in other laboratories (e.g., Witton et al., 2002). Given that it has not been replicated externally (in other studies) or internally (in the present study) the relationship observed may not be a reliable effect. Further investigation is now required to determine if the relationship between 240 Hz FM and reading skills observed here can be found reliably in other settings.

5.9 Visual Attention

In addition to auditory and motion processing problems, some research has demonstrated dyslexics perform more poorly than controls on visual attention tasks

(e.g., Iles et al., 2000; Vidyasagar & Pammer, 1999; Wright & Conlon, submitted a).

These attention deficits, particularly those associated with visual search have been linked to M pathway impairments (Vidyasagar, 1999). Vidyasagar proposed the visual system takes advantage of the fast transmission and spatial coding properties of the M system in the use of a spotlighting mechanism, which provides feedback to lower levels of the visual system. The spotlight is proposed to be crucial for detailed visual processing and correct object perception because it highlights areas for further processing and inhibits object features from other spatial locations. Vidyasagar also proposed the functions of the M-mediated spotlight are crucial for word perception and sequencing during reading. The following section will present results that initially examine the visual attention performance of the dyslexic group as a whole. Analyses which investigate the specific role of the M pathway in attention deficits will then be examined.

5.9.1 Motor reaction time task

An independent groups t-test was conducted to examine simple motor reaction time in the two reader groups. No significant differences between the mean reaction time to visual stimuli in the dyslexic and control groups were found, $t(120) = .014$; $p = .989$ (Cohen's $d = .002$). Therefore, any significant between group differences in terms of response times for serial search that are observed in the following analyses cannot be attributed to simple motor slowness. No further analyses were conducted on these data.

5.9.2 Serial search

Four separate repeated measures analyses of variance were conducted. Two analyses were for the accuracy data from the serial search task in Phase 1 and Phase 4.

The dependent measure was the percentage of correct responses made for each distractor condition when the target was present. In both analyses, all assumptions of the repeated measures analysis of variance were met, except for sphericity. In cases where the assumption of sphericity was violated the Huyn-Feldt correction was applied to the degrees of freedom. The final two analyses were for the response time data from serial search in Phase 1 and Phase 4. The dependent measure was mean correct response time for each distractor condition when the target was present. A square root transformation was performed on these data due to some violation of the homogeneity of variance assumption of the analysis. The Huyn-Feldt correction was applied to the degrees of freedom for the components of the analysis where violation of sphericity occurred.

Accuracy data

There was a significant main effect for number of distractors at Phase 1, $F(3,360) = 53.3; p <.0005$ (Partial $\eta^2 = .308$), and Phase 4, $F(1,120) = 74.9; p <.0005$ (Partial $\eta^2 = .385$). Figure 22 presents accuracy data at Phase 1 and Figure 23 presents accuracy data rates for Phase 4. In general, error rates increased as the number of distractors increased. There were no statistically significant interaction effects involving group at Phase 1, $F(3,360) = .633; p = .594$ (Partial $\eta^2 = .005$), or Phase 4, $F(1,120) = .023; p = .69$ (Partial $\eta^2 = .023$). Nor was there a significant main effect of group at either phase, $F(1,120) = .16, p = .69$ at Phase 1 (Partial $\eta^2 = .001$), and $F(1,120) = .816; p = .368$ at Phase 4 (Partial $\eta^2 = .007$). The response accuracy for both groups was above 80% in all conditions, indicating that none of the participants had difficulty completing the tasks. The high accuracy rate also demonstrates that participants were not trading speed for accuracy.

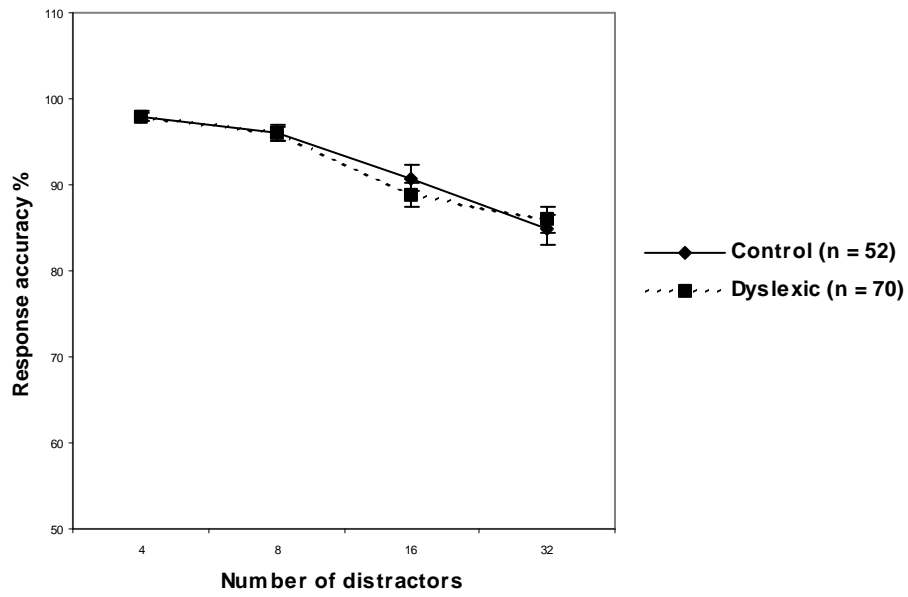


Figure 22. Distractors by group interaction for accuracy data at Phase 1 including standard error bars.

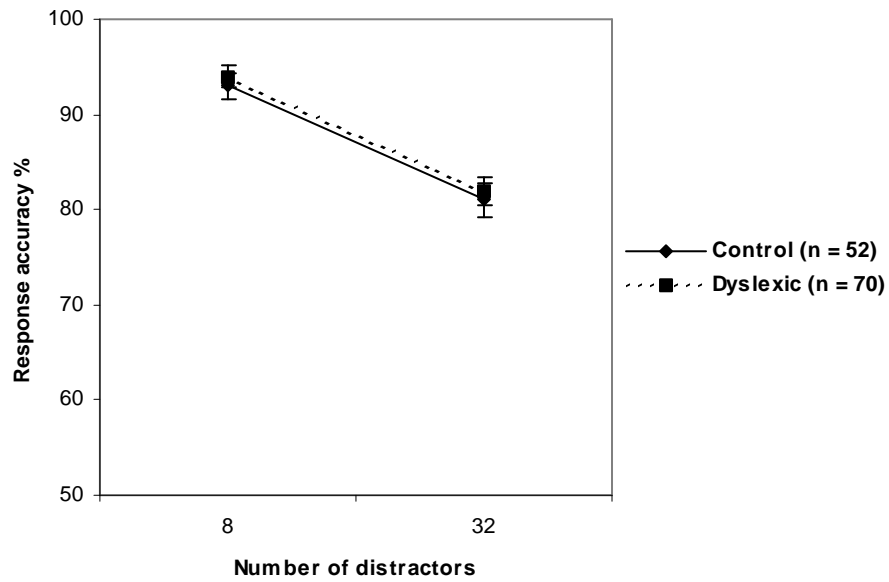


Figure 23. Distractors by group interaction for accuracy data at Phase 4 including standard error bars.

Correct response time

There was a significant main effect of number of distractors at Phase 1, $F(3,360) = 429.05$; $p < .0005$ (Partial $\eta^2 = .78$), and Phase 4, $F(1,120) = 551.7$; $p < .0005$ (Partial $\eta^2 = .821$). Figures 24 and 25 show that there was a linear increase in response time with increasing numbers distractors at both phases. There was no significant interaction between distractors and group at Phase 1, $F(3,360) = 1.38$; $p = .25$ (Partial $\eta^2 = .011$), or Phase 4, $F(1,120) = 1.33$; $p = .25$ (Partial $\eta^2 = .011$). The main effect of reader group was significant at both Phase 1, $F(1,120) = 6.23$; $p = .014$, and Phase 4, $F(1,120) = 5.88$; $p = .017$, with the dyslexic group performing significantly more slowly than control group for all distractor conditions (see Figures 24 and 25). However, the effect sizes (Partial η^2) were small (.049 at Phase 1 and .047 at Phase 4), indicating that the distributions of the two groups were largely overlapping.

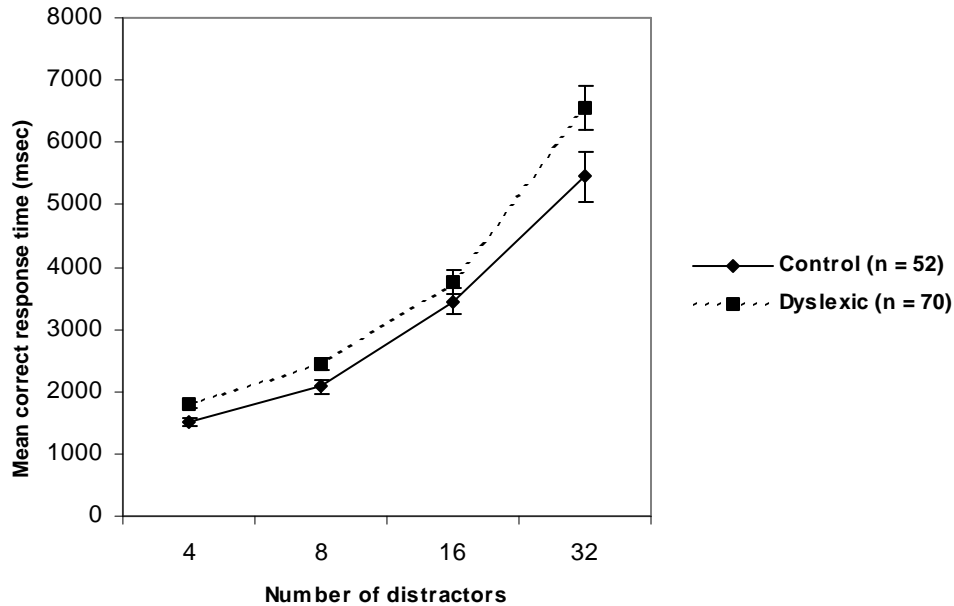


Figure 24. Mean correct response time data at Phase 1 including standard error bars.

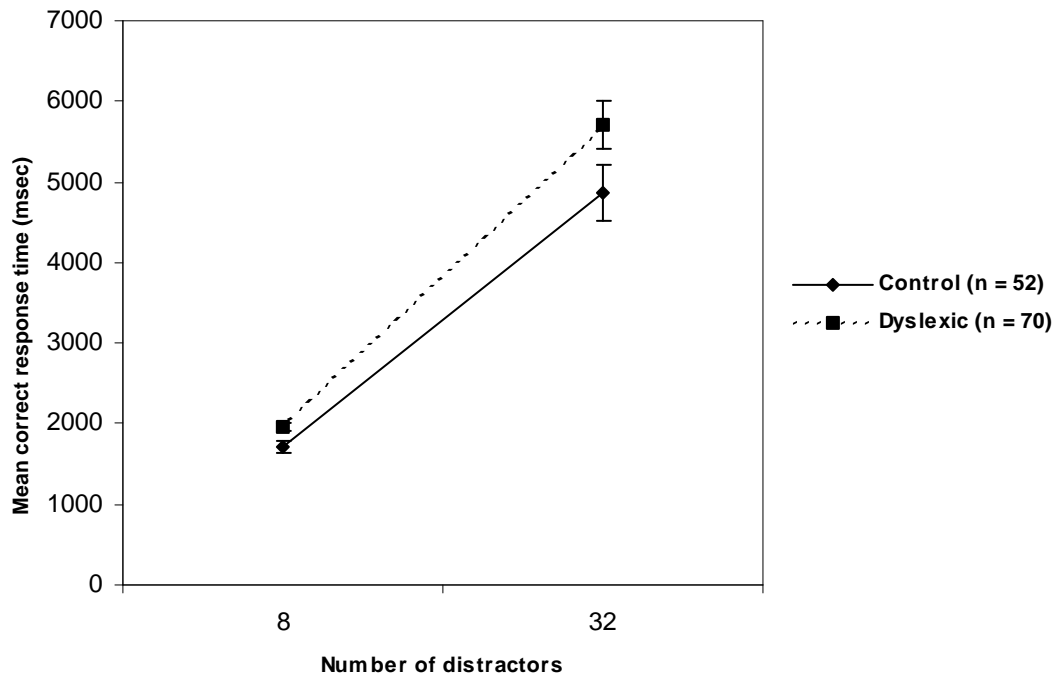


Figure 25. Mean correct response time including standard error bars at Phase 4.

These data provide an important external replication of previous research (e.g., Iles et al., 2000; Vidyasagar & Pammer, 1999; Wright & Conlon, submitted a), which has reported impaired visual search performance in dyslexic groups. Replicating serial search deficits in the dyslexic group across time also provides additional evidence for the reliability of research results. In contrast to Vidyasagar and Pammer, who reported that a small group of dyslexic children had slow serial search only when there were a large (70) number of items in the display, the present study found deficits in the dyslexic group regardless of the number of items in the display. The difference in results across the two studies may result from the different stimuli employed. For example, Vidyasagar and Pammer used targets defined by a conjunction of features (e.g., a purple triangle among purple squares and yellow triangles), which may not have placed large demands upon the attentional spotlight until a large amount of items were

present in the display. The current study used a target that was defined by a unique feature that was not salient, rather than being defined by a conjunction of features. In previous testing conducted with adults, this task was found to be more difficult than a similar conjunction search task to that used by Vidyasagar and Pammer. The serial search task in this study may therefore have placed sufficient demands upon the attentional spotlight even when a small number of items were in the display.

Although a significant between groups effect was found in this study, it is important to note that magnitude of the effect was small at both phases. A deviance analysis was therefore conducted to examine individual performance. Only the 32 distractor condition was used because it is the condition that places greatest demands on the attentional spotlight proposed by Vidyasagar (1999) and is therefore the condition in which any differences in search performance between dyslexics and controls would be most evident. The procedure used to assess deviance for the acoustic and coherent motion tasks was replicated here.

Deviance analysis

Seventeen dyslexics (24% of the sample) had deviant search performance at Phase 1 and 12 (17%) at Phase 4. In the control group, 6 (11.5%) participants had deviant performance at Phase 1 and 5 (9.5%) at Phase 4. Across both phases only 6 (8.5%) of the dyslexic group and 3 (5.7%) of the control group had consistently deviant performance. In addition to the effect size data from the analyses conducted on the entire sample above, these data demonstrate that extrapolating significant between group effects in research studies to all individuals within the dyslexic population based on significant p values alone can be misleading. Visual search impairments exist in only a small number of dyslexic participants rather than being characteristic of the

entire group. These data also demonstrate that slow visual search performance also exists in a small number of control participants.

In addition to investigating individual search performance, the present study aimed to test Vidyasagar's (1999) proposal that impoverished M pathway inputs to visual attention areas in PPC are the cause of the observed serial search deficits in dyslexic groups. On the basis of this proposal the children in this study who had consistent deviant search performance at both phases should also have coherent motion sensitivity impairments. Of the control participants none had motion sensitivity thresholds outside of average limits at either phase of this study. Five of the 6 dyslexic participants also had motion sensitivity thresholds within average limits. Only one dyslexic participant had co-occurring deviant motion processing and serial search performance.

As an additional test of Vidyasagar's (1999) proposal, three groups of children (two dyslexic and one control) were selected from the original sample. One group of dyslexics had motion detection impairments relative to the control group. This group was designated "motion-deficit group" (MDG). The second group referred to as the "non-motion deficit group" (NMDG) had motion detection thresholds within normal levels for the control group. It was predicted that only the MD group would have visual attention impairments relative to the control group. Four separate mixed repeated measures analyses of variance were conducted: two for the accuracy data in Phase 1 and Phase 4, and two for the response time data in Phase 1 and Phase 4. In cases where the assumption of sphericity was violated the Huyn-Feldt correction was applied to the degrees of freedom. A square root transformation was performed on the response time data to stabilise the variances prior to analysis.

Table 18 presents age, IQ and basic reading skills data for these groups.

Analysis of variance tests indicated the groups were adequately matched on age, $F(2,29)$

= .301; $p = .74$, and IQ, $F(2,29) = .076$; $p = .927$. An additional analysis of variance with a planned comparison also demonstrated the two dyslexic groups were adequately matched on reading level at Phase 1, $t(29) = 1.5$; $p = .126$.

Table 18.

Age, IQ and reading data for MD, NMD and control groups.

	MD ($n = 12$)	NMD ($n = 11$)	Control ($n = 9$)
Age	7.64	8.04	8.17
IQ	103	101	101
BRC	27	30.7	57

Note. BRC = raw score on Basic Reading Cluster (Woodcock, 1997).

Accuracy data

There was a significant main effect of number of distractors, $F(3,87) = 19.04$; $p < .0005$, at Phase 1 (Partial $\eta^2 = .396$) and Phase 4, $F(1,29) = 24.4$; $p < .0005$ (Partial $\eta^2 = .457$). The accuracy data at Phase 1 is presented in Figure 26 and the accuracy data for Phase 4 is presented in Figure 27. In general, accuracy of responding decreased with number of distractors. There were no significant interaction effects involving group and number of distractors at either Phase 1, $F(6,87) = .69$; $p = .65$ (Partial $\eta^2 = .046$), or Phase 4, $F(2,29) = .71$; $p = .5$ (Partial $\eta^2 = .047$). There was also no main effect of group at either Phase 1, $F(2,29) = 2.26$; $p = .122$ (Partial $\eta^2 = .135$), or Phase 4, $F(1,29) = .433$; $p = .65$ (Partial $\eta^2 = .029$).

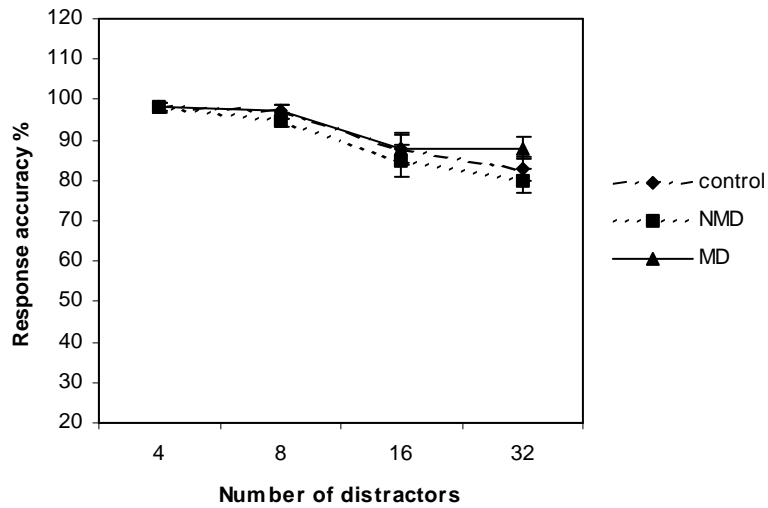


Figure 26. Accuracy data for control, NMD and MD groups at Phase 1 including standard error bars.

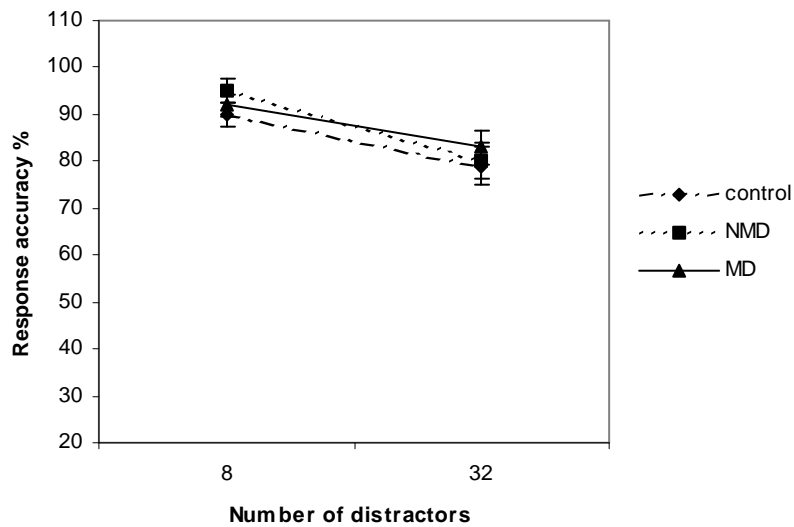


Figure 27. Accuracy data for control, NMD and MD groups at Phase 4 including standard error bars.

Correct response time

A linear increase in response time with increasing numbers of distractors was found at Phase 1, $F(3,87) = 104.5; p < .0005$ (Partial $\eta^2 = .783$), and Phase 4, $F(1,29) =$

142.8; $p < .0005$ (Partial $\eta^2 = .83$). There was no statistically significant interaction involving group and distractors at Phase 1, $F(6,87) = 1.38$; $p = .228$ (Partial $\eta^2 = .087$), or Phase 4, $F(2,29) = .127$; $p = .88$ (Partial $\eta^2 = .009$). Nor was there a statistically significant main effect of group at either phase. At Phase 1, the MD group responded as quickly as the NMD group and matched controls, $F(2,29) = 4.44$; $p = .25$ (Partial $\eta^2 = .09$). The same pattern of results was found in Phase 4, $F(2,29) = .8$; $p = .45$ (Partial $\eta^2 = .052$). These effects are consistent with the finding that motion detection threshold was not related to serial search performance. The response time data for Phases 1 and 4 are presented in Figures 28 and 29 respectively.

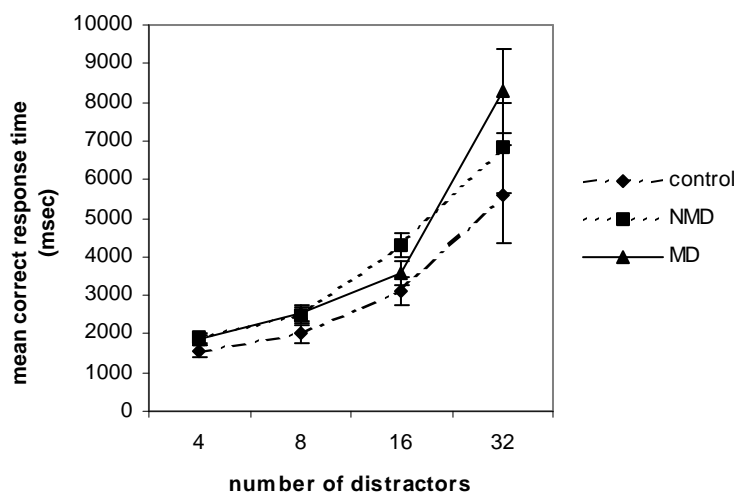


Figure 28. Mean correct response time including standard error bars for control, NMD and MD groups at Phase 1.

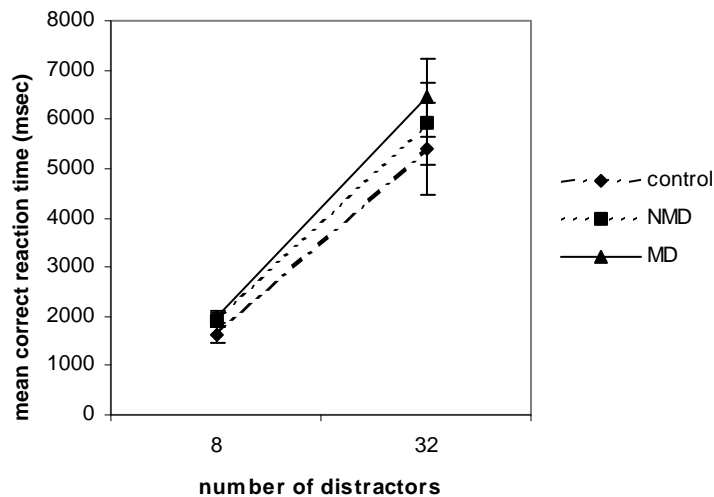


Figure 29. Mean correct response time including standard error bars for control, NMD and MD groups at Phase 4.

These data do not support Vidyasagar’s (1999) proposal that slow serial search results from impoverished M pathway efferents to visual attention areas in PPC. The data demonstrated only one of the six dyslexic participants who were impaired at serial search also had an M deficit (defined as a deviant motion detection threshold). Nor were there significant differences between the response times for serial search in a dyslexic group with M system deficits (MD group) and either a group of dyslexics with no evidence of M system impairment (NMD group) or a control group at either phase of the study. The visual attention impairments seen in some dyslexics therefore seem unrelated to presence or absence of M system deficits.

These data are consistent with a recent study by Wright and Conlon (submitted a), who found poor adult readers had slower visual search performance than skilled readers even under equiluminance conditions where the M system was severely inhibited. The data also receive some support from studies investigating other aspects of visual attention (Heiervang & Hugdahl, 2003; Roach & Hogben, 2004). For example, Roach and Hogben (2004) reported a small group of adult dyslexics ($n = 5$)

who showed performance on the cue-target task (Posner, 1980), indicative of a deficit in orienting spatial attention that did not have corresponding deficits on two measures of M system function: flicker contrast sensitivity and coherent motion detection. The results are also consistent with the research of Heiervang and Hugdahl (2003), who reported that although a dyslexic group performed more slowly than a control group on a cue-target attention task, they showed a clear facilitation for cue information, indicating sensory processing was intact.

In contrast, these data are inconsistent with those of Iles et al. (2000), who found that a group of dyslexic adults previously shown to have motion detection impairments had significantly slower search performance than control readers. Two possible explanations exist for the conflicting results. Firstly, error rates in a number of the tasks employed by Iles et al. approached or exceeded chance levels. The relatively faster search seen in the control and non-impaired dyslexic reader groups may simply have been due to a speed-accuracy trade off in these groups. The second explanation may be that Iles et al. used motion detection thresholds collected at only one point in time to classify participants as having M system impairments. From the results of the current study it is clear there are a substantial number of dyslexic and control readers who show inconsistent performance on measures of sensory processing. Using only one measure of sensory function may therefore increase the probability of a false positive diagnosis of M system impairment.

The question of why some dyslexics appear to have impairments relative to controls on visual search tasks therefore requires explanation. A related challenge is to describe why, when the dyslexic sample were analysed as an entire group, significant between group effects were found; yet when smaller sub-groups of dyslexics were selected, no significant between group differences emerged. One explanation for results seen in this study may be that some participants are less alert to visual stimuli.

Reduced alertness would lead to reduced processing speed for all visual stimuli (Posner, 1978). This would explain why some individuals had slower search times independent of presence or absence of an M system deficit. This explanation could also account for why previous research has shown that poor readers continue to respond more slowly on search tasks when the M system is inhibited (Wright & Conlon, submitted a). However, if less efficient search performance is attributed to reduced alertness, the poor performance seen in some dyslexics would also be evident in a simple reaction time task and this was not the case in this study.

An alternative explanation is that slow visual search performance may be related to other cognitive or neurological mechanisms. The visual attention deficits seen in some dyslexics in this study may arise directly from difficulties at the parietal cortex and may be related purely to attentional processes. Alternatively, slow search performance may be due to difficulty in executive function in an anterior attention system, rather than to a deficit in posterior parietal systems. An anterior attention system is thought to be involved in the performance of all complex tasks. This executive, planning attention system aids in the recruitment of appropriate attentional resources and cognitive strategies (Posner & Deheane, 2000). Such a proposal is consistent with the conclusions of two previous studies that have suggested dyslexics may have difficulty recruiting the cognitive resources necessary for complex task performance (Heiervang & Hugdahl, 2003), or they may have difficulty inhibiting distracting stimuli because of problems with executive function (Bednarek et al., 2004).

5.10 Characteristics of Children with Sensory Deficits

Using a variety of statistical analyses, this study has demonstrated that relationships exist between sensory processing and reading skills. However, sensory processing deficits are not a universal characteristic of dyslexic individuals, although

significant between groups effects were found on the motion and acoustic tests measured at both phases in this study. The next challenge for researchers is to characterise the features of children with and without sensory deficits in order to more fully explain how there may be different pathways to reading failure. A number of previous studies have attempted to explain why sensory deficits exist in only a subgroup of dyslexics. For example, some studies have proposed visual contrast sensitivity and motion detection deficits only exist in a sub-type of dyslexia with poor phonological decoding skills (Slaghuis & Ryan, 1999; Borsting et al., 1996). However, other studies have failed to find evidence for this relationship (e.g., Williams et al., 2003; Ridder et al., 2001). Other studies suggest sensory deficits exist only in dyslexics with co-existing oral language disorder (Heath et al., 1999), while still others have argued the deficits observed are the result of inattention in dyslexics while performing psychophysical tasks (Roach et al., 2004; Stuart et al., 2001). This study considered the definition of dyslexia as an alternative hypothesis.

In defining dyslexia for purposes of the previous analyses, the current study employed an operational definition for low reading achievement, which set limits on reading impairment and IQ. Such a definition does not necessarily separate between dyslexic children whose reading problems are presumed to have a biological basis and children for whom reading difficulties are caused by environmental factors, such as lack of exposure to text or inappropriate reading instruction. Clay (1987) argued that failure to control for the child's educational history is a major impediment to diagnosis of dyslexia. Clay proposed that virtually all studies which have sought to discover the underlying neurological mechanisms in dyslexia have been confounded by this problem, because the manifest symptoms of poor pre-reading experience, inadequate exposure to text or inappropriate reading instruction can mimic the effects of neurologically based cognitive deficits in dyslexia (Clay, 1987).

To illustrate this point, the results of a study conducted by Vellutino and colleagues will be summarised. Vellutino et al. (1996) selected 76 children identified by class teachers as poor readers. Poor readers were matched with a skilled reading classmate and both were given an extensive battery of cognitive and reading ability tests. All poor readers had reading skills below the 15th percentile on word identification or nonword reading tests, and an IQ of at least 90. That is, they would all qualify for diagnosis of dyslexia based on the initial operational definition of dyslexia used in this study and in the majority of studies in the reading literature. The poor readers received thirty minutes of daily individual reading instruction. The reading skills of the participants were assessed at four points over a two-year period. The growth in reading skills for these children is shown in Figure 30.

The poor readers were re-classified into sub-groups on the basis of their response to remediation (reading growth). A large portion of the children made some improvements, but Figure 30 shows their reading skills to still be substantially below average levels. This is particularly evident in the “very low growth” (VLG) and “low growth” (LG) groups. Many of these children continued to have basic reading skills below the 15th percentile and would therefore continue to still be classified as dyslexic using the operational definition adopted in this and many other studies. However, ~25% of the children initially identified as poor readers by teachers and who also initially fell below the limits set for reading ability, made substantial gains in response to reading instruction. This is best typified by the “very good growth” (VGG) group, who after approximately eighteen months of reading instruction had an average basic reading score in the 63rd percentile. The average basic reading score in the “good growth” (GG) group after a similar period also fell into the average range (43rd percentile). These data indicate there is a possibility of false positive diagnosis of dyslexia using traditional criteria. The data also demonstrate that accounting for

instructional factors by virtue of assessing growth in response to reading intervention may be a useful method of distinguishing between dyslexic children whose reading difficulties are presumed to have a biological basis and those children whose reading difficulties have an environmental basis.

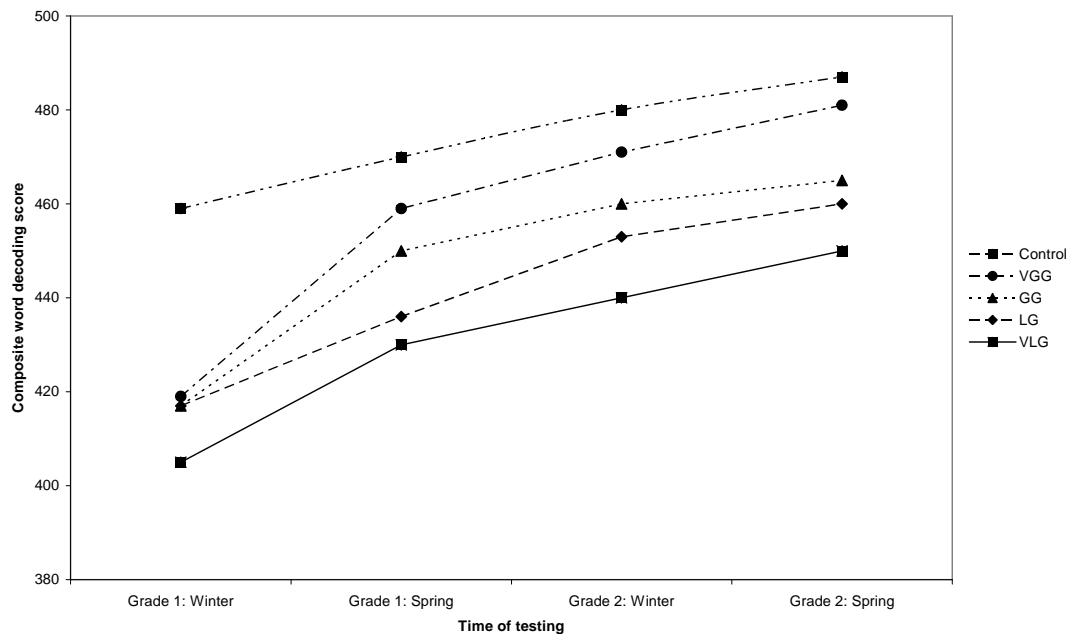


Figure 30. Reading growth of control and poor readers over a two-year period in response to reading intervention.

Note. VGG = very good growth, GG = good growth, LG = low growth, VLG = very low growth. Adapted from Vellutino et al., 1996

Almost without exception, the published literature that has investigated sensory processing in dyslexia has employed discrepancy or modified discrepancy criteria from a single testing evaluation. It is therefore highly probable that a number of participants who were in fact not dyslexic were included in these studies. It was proposed that this can explain why studies typically find only a sub-group of dyslexics have sensory

impairments, and why some studies fail to find sensory deficits at all. The current study re-investigated sensory processing after controlling for the educational history of the children in the dyslexic group by re-evaluating their reading skills after they had been engaged in nine months of school-based reading intervention. Specifically, it was predicted that only those children who failed to respond to intervention would have sensory impairments.

As a 'first-cut diagnostic' in distinguishing between dyslexic and non-dyslexic poor readers, a growth curve analysis was conducted to compare the progress of the poor readers relative to control children on the BRC, in response to a school-based intervention program. The intervention was conducted by remedial teachers in small group settings. Each child received phonological based instruction that focused on developing sound-letter knowledge and word level decoding skills. Hatcher et al. (1994) have demonstrated this form of instruction to be the most effective for primary age children with reading difficulties. Each child received two intervention sessions per week for the whole school year.

Following the method of Vellutino et al. (1996) the growth rates of participants were obtained by specifying reading scores as a function of time. The Rasch based (W) scores from the BRC of the WDRB (Woodcock, 1997) were used as an estimate of reading ability at given points in time. Four measures were obtained: one in each of the four school semesters. For each participant, a linear regression analysis was conducted with time in weeks between Phase 1 and Phase 4 as the independent variable and the BRC W score as the dependent measure. Slopes for the dyslexic group were rank ordered and the entire group was classified into three groups according to their relative slopes on the continuum. These groups were labelled "good growth" (GG), "low growth" (LG) and "very low growth" (VLG).

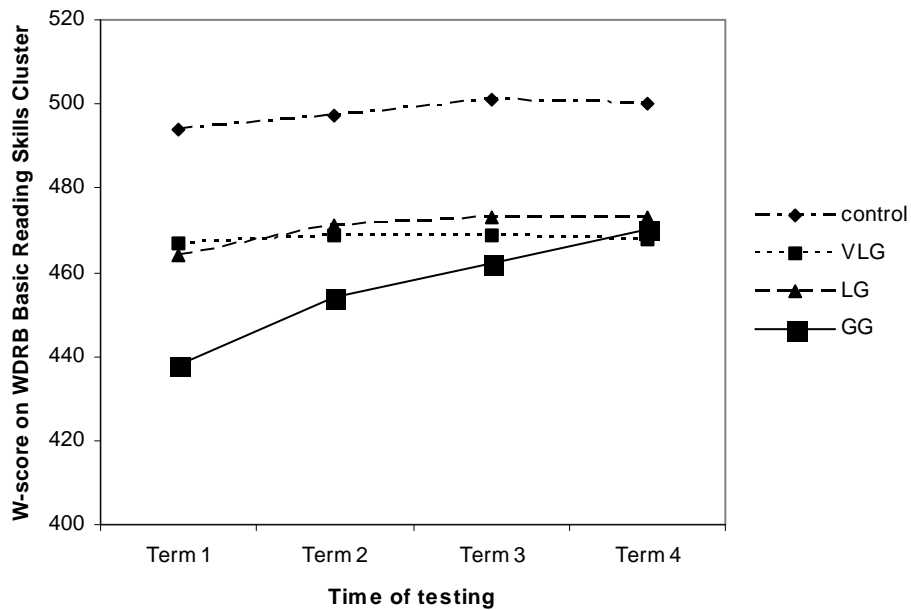


Figure 31. Growth curves for W-scores on WDRB Basic Reading Skills Cluster for control and poor readers. VLG = very low growth; LG = low growth; GG = good growth.

Figure 31 presents growth curves for BRC W scores. It can be seen that the VLG group made almost no progress in reading across the year, while the LG group made only minimal progress. The GG group made substantial progress, although as can be seen from their reading scores at the end of the year, they still had substantial reading difficulties relative to the control group. Figure 31 shows the children in the GG group were initially the poorest readers in the study. Children in the GG group demonstrated the greatest growth in reading skills over the course of the study, while children in the VLG group showed the least amount of progress. Therefore, the best test of the proposal that sensory deficits would only exist in children who failed to respond to

intervention would be to assess the performance of these two groups relative to controls on measures of auditory and visual processing.

5.11 Sensory Processing in Children Who Responded Differently to Intervention

Three separate analyses of variance were conducted to compare the performance of the GG ($n = 9$) and VLG ($n = 9$) groups to controls ($n = 9$) matched as closely as possible on age and IQ on Phase 4 thresholds for 2 Hz FM, 240 Hz FM and coherent motion. Due to difficulties in matching the groups on age – the VLG group were older than the GG group – age was always entered as a covariate in the analysis. All assumptions of the analysis of variance were obeyed. There was a significant main effect of group for all three stimulus tasks: 2 Hz FM, $F(2,23) = .3.69$; $p = .04$ (Partial $\eta^2 = .243$), 240 Hz FM stimulus, $F(2,23) = 4.14$; $p = .029$ (Partial $\eta^2 = .265$) and coherent motion, $F(2,23) = 3.3$; $p = .05$ (Partial $\eta^2 = .224$). However, post hoc analyses indicated that it was only for the 240 Hz FM stimulus that the VLG group have significantly lower sensitivity than the control group. For the 2 Hz FM and coherent motion stimulus tasks the data ran contrary to predictions, with the GG group having significantly lower sensitivity than the control group (see Figures 32-34). The results do not therefore appear to follow any logical pattern and demonstrate that response to the intervention does not separate between individuals with and without sensory processing deficits. It could be argued that the school-based literacy intervention, which was conducted in small groups, was not intensive or structured enough to adequately separate between children whose reading difficulties have a neurological basis and those who have difficulties due to their educational history. Indeed, a number of studies (e.g., Vellutino et al., 1996) have demonstrated that one-one instruction is more effective than literacy instruction conducted in small group settings. However, any inadequacy in the reading instruction the dyslexic participants received would only underestimate the effect

reported here. While a different intervention programme may have led to greater gains in the both the GG and VLG groups, it could reasonably be expected that the greatest gains would still be seen in the GG group. Comparing the GG and VLG groups can therefore still be considered a valid test of the hypothesis that response to intervention can distinguish between those with and without sensory processing deficits.

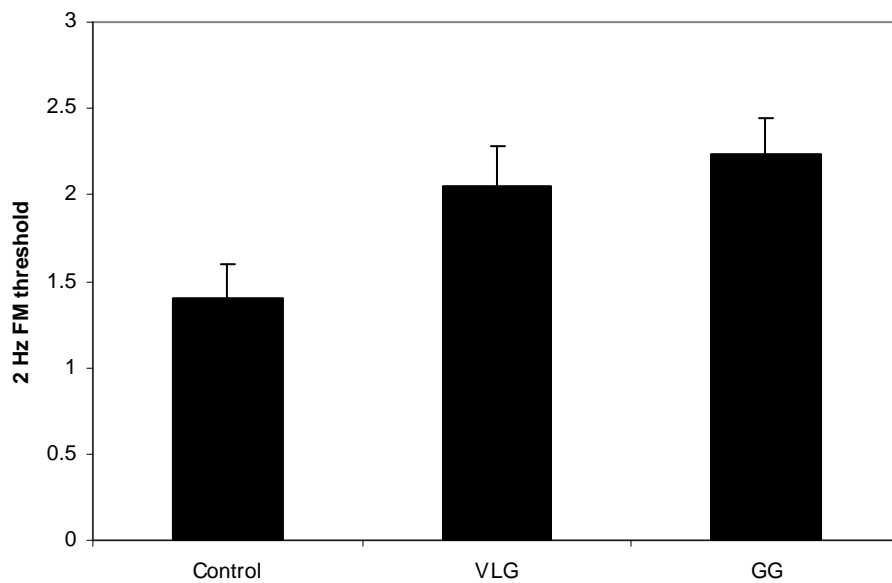


Figure 32. Means and standard errors for control, VLG and GG groups for 2 Hz FM at Phase 4.

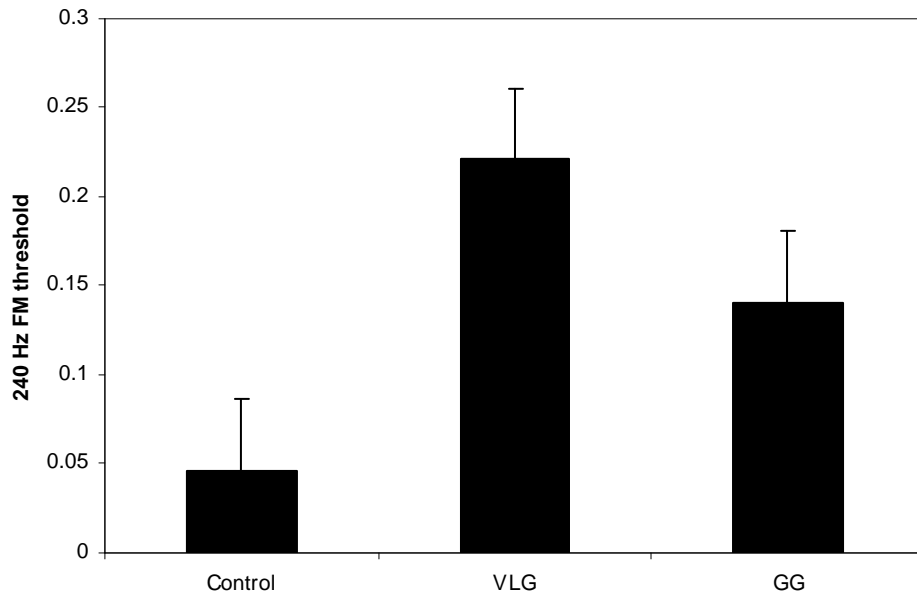


Figure 33. Means and standard errors for control, VLG and GG groups for 240 Hz FM at Phase 4.

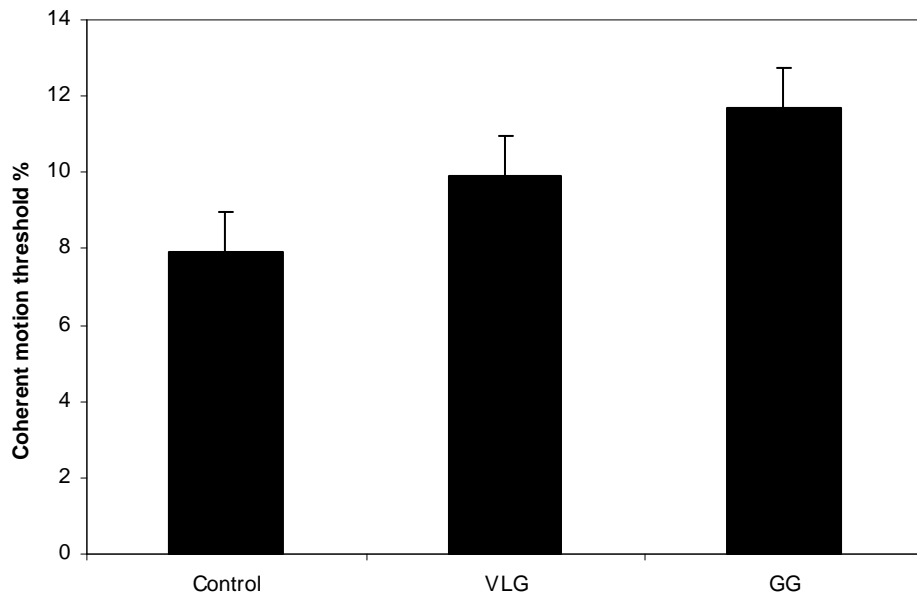


Figure 34. Means and standard errors for control, VLG and GG groups for coherent motion thresholds at Phase 4.

5.12 General discussion

There are a large number of published studies that have reported sensory processing deficits in dyslexic compared to control groups. A number of studies have also reported that significant relationships exist between measures of sensory processing and measures of reading skill (e.g., Conlon et al., 2004; Huslander et al., 2004; Witton et al., 1998; Witton et al., 2002; McAnally & Stein, 1997; Menell et al., 1997; Edwards et al., 2004; Talcott et al., 1999; Talcott et al., 2003; Wilmer et al., 2004). However, there are also a number of studies that have failed to find these relationships between dyslexia and sensory processing (e.g., Kronbichler et al., 2002; Hill et al., 1999; Hill & Raymond, 2002). Interpretation of these conflicting results has been complicated by the wide range of sensory processing tasks and task parameters that have been employed across studies. The current study sought to investigate the reliability of research results showing sensory deficits in dyslexic groups through both external and internal replications of measures of statistical and practical significance (e.g., *p* values and effect sizes). To avoid the previously mentioned problems of comparing results across studies that have used different sensory measures, the current study also employed the same auditory and visual processing tasks as several recent and widely referenced investigations (e.g., Hansen et al., 2001; Talcott et al., 2003; Witton et al., 2002). Although external replications have been conducted previously, no study to date has attempted to internally replicate sensory processing data in the same participants across time. The current study therefore built upon previous research by providing data on the stability of the results across time. The results of these initial analyses are discussed in the following sections. The auditory and visual processing data are examined separately.

5.12.1 Consistency with previous research – auditory processing

Previous research examining the auditory processing profiles of dyslexic groups has reported that the impairments are specific to temporal stimuli (e.g., Witton et al., 1998; Witton et al., 2002). For example, Witton et al. (2002) reported that a group of dyslexic adults were less sensitive than a control group to the temporal stimuli 2 Hz FM and 20 Hz AM, but not to the control stimulus 240 Hz FM, which is detected on the basis of spectral cues. The current study did not replicate these findings. Instead, the auditory impairment observed in the dyslexic group can be better described as general rather than specific to processing temporal stimuli. The dyslexic group were significantly less sensitive than the control group to the non-temporal control variable 240 Hz FM, in addition to the temporal variables 2 Hz FM and 20 Hz AM. The internal replication of these data across time, both in terms of the significant between group differences and the strength of the effect sizes, demonstrate the reliability of the results.

The inconsistency between the present results and those of previous studies that have employed the same auditory tasks (e.g., Witton et al., 1998; Witton et al., 2002) may result from the different levels of statistical power employed. For example, although Witton et al. (2002) did not find a statistically significant between groups effect for the non-temporal 240 Hz FM variable, the effect size for that stimulus was in the moderate to strong range (Cohen's $d = .59$). The current study had power of $\sim .89$ to find this size effect, while the Witton et al. (2002) study had low power ($\delta = .44$) to find this effect size. The inconsistent results between the studies can therefore be explained in terms of the statistical power of the individual studies. Further research is now needed, which seeks to replicate the present findings using the same methodology. When interpreting future data, care should be taken to take the effect size and power of study into account before drawing conclusions.

In addition to providing new evidence that the auditory deficit in dyslexics is general rather than temporal, the results of the current also permit investigation of a number of alternative explanations for poor performance on the auditory processing tasks. For example, Hari, Valta et al. (1999) proposed that dyslexics might have an impairment in a short-term cognitive buffer, which may cause successive sounds to interfere with perception of previous and successive sounds within a brief 'cognitive integration window'. The acoustic tasks used in this study required participants to discriminate between two auditory tones separated by an ISI of 500 milliseconds. This procedure required a perceptual memory of the first sound to be retained and compared to a subsequent sound for successful performance. Impairment in the cognitive buffer proposed by Hari et al. may therefore lead to poor task performance.

Based on Hari, Valta et al.'s (1999) proposal, impairment in the cognitive buffer would lead to poor performance on all of the auditory tasks employed in the current study, regardless of the nature of the stimulus itself (i.e., whether the stimulus was temporal or spectral in nature) because they place identical demands on the cognitive buffer. The current data does not support this proposal, as few participants were impaired for all the auditory tasks. In fact, most participants tended to have reduced sensitivity on only one psychoacoustic task. Thus, the data from the current study suggest that impairment in the cognitive buffer proposed by Hari, Valta et al. may be excluded as an explanation for the auditory processing impairments found here.

An alternative explanation is that deficits in working memory in the dyslexic group can explain poor performance on auditory and other psychophysical tasks. It should be noted that a distinction exists between working memory and the cognitive buffer proposed by Hari, Valta et al. (1999). The cognitive buffer is presumed to be a component of a specific neural processing system for auditory signals. In contrast, working memory is a general system thought to be involved in a wide range of mental

tasks. There is currently no neurological evidence that demonstrates working memory plays a crucial role in auditory processing tasks. Nevertheless, a number of recent studies have suggested that a common reliance on working memory may explain the apparent lack of sensitivity on auditory processing tasks in dyslexic groups (e.g., Ben-Yehudah & Ahissar, 2004; Witton et al., 2002). In the most influential model of working memory, Baddeley and Hitch (1974; see also Baddeley, 1986) proposed working memory to consist of a central executive (CE), which serves as a control mechanism, and two slave systems for temporary storage of verbal and visual information respectively (the phonological loop and visuo-spatial sketchpad). The CE is responsible for important high-level cognitions, including planning, co-ordinating the flow of information through working memory and retrieving knowledge from long-term memory (Pickering & Gathercole, 2001). The capacity of this system is referred to as working memory capacity (Just & Carpenter, 1992), while the capacities of the phonological loop and visuo-spatial sketchpad are referred to as short-term storage capacity (de Jong, 1998).

Dyslexics are impaired on tasks assessing the phonological loop, indicating they have less short-term storage capacity within this system (Pickering & Gathercole, 2001). Recent evidence has also demonstrated that dyslexics have a deficit on tasks requiring the operation of the CE (de Jong, 1998). Although working memory remains poorly specified (Baddeley, 1996), one recent suggestion is that attention switching is the critical characteristic of CE tasks. Children are required to alternate their attention between the storage component (phonological loop and visuo-spatial sketchpad) and the processing component (central executive). The psychophysical procedure for the auditory processing tasks used in this study required short term storage capacity (for the two tones) and at least two possible CE functions: (a) comparing the two tones to identify the modulated tone, or (b) comparing both tones to a representation of a

modulated tone held in long-term memory. Conceivably, therefore, a participant with a deficit in CE function (i.e., a dyslexic) may have difficulties on the psychoacoustic tasks because of the task demands, rather than because that individual has reduced sensory sensitivity. However, in common with the cognitive buffer explanation discussed above, one would expect that if working memory impairments are the source of deficits on the auditory tasks, then a participant with reduced sensitivity on one task should also be impaired on the other three tasks, which place the same demands on working memory. As discussed above, this was not the case in the current study. Working memory therefore seems an unlikely explanation for the auditory deficits found in the present study.

Although the results of the present study failed to replicate previous findings of a temporal auditory impairment in the dyslexic group, sensitivity to the temporal measure 2 Hz FM did account for significant portions of the variance in phonological and overall reading skill, even after accounting for IQ and vigilance. The amount of variance accounted for by the 2 Hz FM measure was typically small (between 1.7% - 6.9%). However, two factors provide evidence of the reliability of these relationships. The first is that these data replicate previous studies, which have reported similar size relationships between temporal auditory measures and reading skills (e.g., Witton et al., 1998; Witton et al., 2002; Talcott, Witton, McLean et al., 2000; Talcott, Witton, Hebb et al., 2000). In addition to this, the data were replicated internally across time. Although it appears as if the relationships observed between the temporal variable 2 Hz FM and reading skills are reliable and stable across time, it remains to be established how poor temporal processing affects reading.

The most obvious mechanism by which poor auditory temporal processing may affect phonology and reading skills is through speech perception and has been discussed extensively previously (see Goswami et al., 2002; Richardson et al., 2004; Witton et al.,

2002; Witton et al., 1998). The slowest gross modulations in the speech signal, such as 2 Hz FM, carry phonemic and syllabic information (Shamma, 2003). Impairment in processing these gross modulations in young children may therefore lead to difficulties in adequately specifying phonological representations, and consequently to difficulty developing phonological awareness, knowledge of the alphabetic principle and fluent reading skills. In these children, the distal cause of reading difficulties may therefore be a deficit in bottom-up, central auditory processing.

In contrast to previous research, the non-temporal control measure 240 Hz FM was also significantly related to reading skills at Phase 1. Thresholds for 240 Hz FM accounted for 3.7% of the variance in orthographic coding skill and 3.1% of the variance in overall reading skill. These results are inconsistent with all previous studies which have included sensitivity to 240 Hz FM as a control measure (e.g., Talcott, Witton, McLean et al., 2000; Witton et al., 1998; Witton et al., 2002). The relationship observed between the control measure and orthographic coding and overall reading skill at Phase 1 might suggest that common task related factors can explain the relationship between performance on the auditory processing tasks and reading skills. However, 240 Hz FM was not related to phonological skill, nor was the relationship replicable across time. The failure to internally replicate the relationship, and previous failures to find the same effect in other laboratories suggest that the effect may not be reliable.

5.12.2 Consistency with previous research – visual processing

Previous research (e.g., Conlon et al., 2004; Cornelissen et al., 1995; Hansen et al., 2001; Martin & Lovegrove, 1987; Talcott et al., 2003; Wilmer et al., 2004) has demonstrated that dyslexic groups are significantly less sensitive than controls to dynamic stimuli processed by the M system. The strongest evidence for M system deficits in dyslexics comes from studies that have employed coherent motion detection

tasks. In the current study, the dyslexic group had reduced sensitivity to coherent motion compared to the control group. These data therefore provide a direct external replication of those previous studies that have found reduced motion sensitivity in dyslexic groups. The data also provide a direct replication of a number of previous studies that have employed the same task as the present study (e.g., Conlon et al.; Hansen et al.; Talcott et al.; Wilmer et al.). In addition to replicating these previous data externally, the current study demonstrated that findings of coherent motion deficits in dyslexic groups can be replicated across time in the same participants. The data from the current study therefore add important new evidence for the reliability of findings of motion detection deficits in dyslexic groups.

A large body of evidence has located visual area V5 as the site at which the visual system processes coherent motion. The main input to V5 is derived from local motion sensitive cells in the M system. The efferent responses of these M cells project along the dorsal stream to V5 where perception of global motion is performed. Previous research has demonstrated that abnormalities exist within the M layers of LGN in dyslexic brains (Galaburda & Livingstone, 1993; Livingstone et al., 1993). There is also some evidence from psychophysical studies that dyslexic groups process stimuli detected by the M system at LGN less efficiently than controls (e.g., Slaghuis & Ryan, 1999; Martin & Lovegrove, 1987). A deficit in M cells sensitive to local motion at lower levels of the visual system, such as at LGN, may therefore lead to less motion information reaching V5 and less V5 neurons being activated, consequently making it more difficult to detect global motion.

An equally plausible explanation is that some dyslexics have a similar deficit in the organisation and structure of cells within V5 as has been found in the M layers of LGN. Coherent motion is detected at V5 by summing the responses of individual cells, which are tuned to a specific direction of motion in a particular section of the visual

field. If the summed responses of the individual cells exceed a given critical threshold, the visual system can perceive global motion in the stimulus. If fewer cells are present in V5, or the size of these cells are smaller than is typical, the global motion signal perceived by the visual system may fail to exceed the critical perceptual threshold.

In addition to finding significant motion sensitivity deficits in the dyslexic group, the current study also found that thresholds for coherent motion were significantly related to overall reading skill, phonological processing and orthographic coding skill. Motion detection thresholds accounted for between 2.25% and 7.5% of the variance in the summary measures READING, PHONOLOGY AND ORTHOGRAPHY, even after accounting for IQ and vigilance. These data externally replicate previous findings, which have reported similar relationships between coherent motion thresholds and reading measures (e.g., Conlon et al., 2004; Talcott et al., 1998; Talcott et al., 2002; Talcott, Witton et al., 2000). The size of the relationships was also replicated internally across time in the same participants. The current data therefore present important evidence for the reliability of the relationship between visual processing of motion and reading skills. The data do not support the proposal that motion sensitivity is independently related to the ability to code the orthographic features of words (e.g., Stein, 2001; Talcott, Witton et al., 2000). Motion thresholds were related to both orthographic and phonological skill, and auditory thresholds also accounted for unique variance in orthographic skill. These results are consistent with other research that has demonstrated orthographic skill to be related to both visual and auditory processing (Talcott et al., 2002). Similar relationships between coherent motion sensitivity and phonological and word reading skills have also been reported by other investigations (Conlon et al., 2004; Huslander et al., 2004; Talcott et al., 2002; Witton et al., 1998). It therefore appears as if the relationship between visual motion detection and reading is more general than the specific relationship between visual skills

and orthographic coding proposed previously (e.g., Cornelissen et al., 1998; Cornelissen, Hansen, Gilchrist et al., 1998; Stein, 2001; Talcott, Witton, et al., 2000).

One possible explanation for the link between motion processing deficits and reading postulates a mediating effect of visual attention (Vidyasagar, 1999).

Vidyasagar proposed that the inputs of the M pathway, including the motion sensitive area V5, to visual attention areas in PPC are crucial for efficient use of an attentional spotlight. This spotlight may be important for reading to allow for correct binding of word features, letter sequencing and correct sequencing of words within sentences.

Consistent with this theory, previous research has demonstrated that dyslexic groups perform visual tasks that require the attentional spotlight, such as serial search, less efficiently than controls (e.g., Iles et al., 2000; Vidyasagar & Pammer, 1999; Wright & Conlon, submitted a). The current study replicated these previous findings of visual search impairments in dyslexic groups. In addition, slow serial search performance in the dyslexic group was replicated internally over time, adding further weight to the evidence for the reliability of these data. However, the effect sizes for the significant between group differences were small (Partial $\eta^2 = .049$ at Phase 1 and Partial $\eta^2 = .047$ at Phase 4). This demonstrates that although there was an overall significant between groups effect, there was also a large amount of overlap between the serial search performance of the dyslexic and control groups. In fact, when the serial search data were subjected to the same deviance analysis procedure conducted for the other psychophysical data, only 8.5% of the dyslexic group had impaired search performance across both phases. Furthermore, 5.7% of the control group also had serial search impairments across both phases of the study.

Although the current data demonstrate that impairments on visual attention tasks, such as serial search, exist only in a small sub-group of participants, these data alone do not directly test Vidyasagar's (1999) hypothesis. To do this, the current study

investigated the relationship between motion processing and serial search performance. An initial analysis demonstrated that only one dyslexic participant who showed impaired serial search performance had a co-existing deficit in motion sensitivity. None of the control participants with search impairments had co-existing motion deficits. In a second between groups analysis, no significant between groups differences existed in the search functions of a dyslexic group with motion processing deficits, a dyslexic group with normal motion processing performance and a control group. Therefore, the current data do not support Vidyasagar's prediction. In the current study, deficits in visual attention existed independently of a deficit in processing visual motion in the M system.

Although these data appear to rule out visual attention of this type as the link between poor M pathway or motion processing and reading, they do not rule out the possibility that the neurological or cognitive deficits that led to difficulties on the serial search task for some participants also affect reading. Vidyasagar suggested that deficits in using the attentional spotlight might lead to incorrect combinations of word features. However, in this study and in previous investigations (e.g., Iles et al., 2000; Vidyasagar & Pammer, 1999; Wright & Conlon, submitted a) the dyslexic group did not differ in accuracy of target identification compared to the control group; they were simply slower when performing the task. Furthermore, slow serial search was also seen in some control participants who did not exhibit any reading difficulties. Thus, it seems unlikely that the cognitive or neurological impairments that lead to difficulties with serial search would also cause perceptual problems (such as incorrectly combining word features) when reading. An alternative is that slow serial search may signal difficulties in the rate at which visual attention can be directed along a line of text or the rate at which letters in a written word can be sequenced. The deficits observed in serial search in some participants in this study may therefore be more related to reading fluency rather than

reading accuracy. Inefficient spotlighting in dyslexic children may add another layer of difficulty to the reading process, over and above that caused by difficulties in acquiring alphabetic skills. In a skilled reader, inefficient spotlighting may simply cause reading to be a more effortful process, without affecting reading accuracy. While these hypotheses are purely speculative at this point, the prima facie involvement of visual attention processes in reading make it worthwhile investigating in future studies.

5.12.3 Sensory deficits: universal or individual difference?

If the present study were to follow the tradition that has existed in the dyslexic literature (e.g., Conlon et al., 2004; Hansen et al., 2001; Witton et al., 2002), on the basis of the current data it would simply be concluded that dyslexics as a whole have auditory and visual processing deficits. However, the strength of the effect sizes obtained in the current study as well as visual inspection of the data, clearly demonstrates that sensory processing deficits are not a universal characteristic of dyslexia. A number of other investigations have also acknowledged that sensory impairments only exist in a sub-group of dyslexics (e.g., Tallal, 1980; Edwards et al., 2004; Ramus et al., 2003). Acknowledging that this is the case raises a number of challenges for dyslexia researchers. The first of these challenges is to determine the proportion of dyslexics who have sensory impairments and also whether sensory deficits exist in skilled readers.

The current study investigated this issue by conducting a deviance analysis for the auditory tasks 2 Hz FM and 240 Hz FM and the coherent motion task. The results demonstrated that only 5%, 18% and 17% of the dyslexic group had consistently deviant thresholds across both phases of the current study for the 2 Hz FM, 240 Hz FM and coherent motion tasks respectively. In addition, 2% of the control group had consistently deviant thresholds for 2 Hz FM across both phases and 4% of the control

group were impaired on either the 240 Hz FM or coherent motion tasks. This is a lower incidence than in previous studies, where estimates have ranged from 30-60% (e.g., Edwards et al., 2004; Ramus et al., 2003). The results of previous studies are actually consistent with the current study when data from only one phase was examined. The lower incidence found in the current study can therefore be considered to result from accepting as deviant only those participants who had deviant thresholds at both phases. This strategy was adopted to avoid classifying as deviant, participants who performed poorly at one time or the other because of factors unrelated to sensory sensitivity. These data demonstrate that the majority of the dyslexic sample had reading difficulties without any sensory processing deficit, indicating a sensory deficit is not necessary to cause dyslexia. Nor is a sensory deficit sufficient to cause dyslexia, as a number of control participants were observed to have abnormal thresholds. Nevertheless, a large number of both dyslexic and control participants *did* show deviant sensory performance at one point in time. A second challenge is therefore to explain why this occurred.

The most obvious explanation for the inconsistent performance of some participants is that the elevated thresholds shown at one point in time were due to greater distractibility or lack of attention in these individuals. However, such an explanation may be overly simplistic. A more complete explanation may be that the pattern of inconsistent responding observed in the present study was due to the nature of the tasks and the method by which threshold estimates were obtained. Psychophysical tasks, such as those employed in this and other studies, can last for as long as ten minutes and contain long sequences of identical trials that have little novelty value. The demands that such a task places on vigilance and inhibition resources could conceivably lead to errant responding at any point throughout the task; particularly in children. Nor are problems with vigilance and distractibility the only factors that may be involved in errant responses. As Roach et al. (2004) have pointed out; to respond to any given item

the participant must perform a number of functions. For example, they must interpret task instructions, identify and monitor relevant aspects of the stimulus; form a decision based on the available information held in memory and generate an appropriate response. Difficulties or inconsistencies with any of these functions throughout a task could lead to an errant response that does not reflect the sensory processing abilities of the individual. A coherent motion task example will now be used to describe how errant responding on a given trial could affect the reliability of threshold measurement. Note that the same staircase procedure was used for the auditory tasks in this study and the problems identified below could equally apply to the auditory data.

In this study, motion sensitivity thresholds were estimated by calculating the mean coherence of the last 8 of 10 reversals (incorrect trials) during the staircase procedure. As only the last 8 reversals are included in the threshold measurement, an errant response at the beginning of the task (possibly due to lack of familiarity with the task or strategy development) will have no effect on the reliability of the threshold estimate. However, an errant response in the remainder of the task will inevitably lead to error in the estimate. If this occurs once at a point close to actual threshold for that participant, only one “incorrect” reversal will be made and the error in threshold estimate averaged across 8 reversals will be small. In contrast, a number of errant responses (particularly if they are made well above threshold) will lead to a large amount of error in the threshold estimate averaged across 8 reversals.

The threshold measurements used to obtain psychophysical thresholds in many studies are therefore susceptible to error when a participant responds randomly on any given item. Due of this possibility, collecting threshold measurements at separate points in time may be a better way of investigating the presence or absence of sensory impairments in individuals, rather than the single threshold measurements that are typically gathered now. Many studies typically collect data on two staircase

measurements in a single testing session to reduce error. Estimating thresholds at two separate points in time is simply an extension of this procedure. An alternative method may be to employ the techniques of signal detection theory to estimate the point at which individuals are most sensitive to auditory or visual stimuli. Participants would be presented with a number of trials at pre-set step sizes between the known upper and lower limits of sensitivity on a particular task (this is another reason why normative data will be a useful addition to the literature). By applying a psychometric function to the data obtained, the researcher could estimate the point at which the participant is most sensitive. Due to the large number of trials presented at each step size, and because adaptive methods (vulnerable to errant trials) are avoided, the use of signal detection theory potentially reduces the impact of a lapse in vigilance on a particular sensitivity estimate. The disadvantage of using signal detection theory is that by necessity it involves presentation of a large number of trials. Consequently, testing time is increased, as is the need for vigilant and motivated participants. Its suitability for use with children requires investigation.

A related problem is that there is no normative data available for the sensory processing tasks. This necessitates the use of the control group mean as a benchmark for deviant performance. Inevitably therefore, all studies will use different criteria to define deviance. This method has the potential to introduce a substantial amount of error into a deviance analysis, such that it may over, or even under estimate the number of children who have true sensory processing deficits. Therefore, in order to fully answer the question of how many dyslexic individuals have true sensory deficits, research is required to develop normative data for these tasks. Future research should also address the issue of how best to define deviance in sensory processing. In this study, deviance was set at 1.65 SD above the mean of the control group. Ramus et al. (2003) used the same criteria, however, other studies have employed less stringent cut-

offs. For example, Edwards et al. (2004) and Wilmer et al. (2004) adopted criteria of 1 SD above the control group mean to define deviance on sensory tasks. Normative research may assist in resolving this issue because it will allow performance ranges to be calculated across the whole population at different age ranges, as they are in many cognitive tests (e.g., WISC-IV, Wechsler, 2003). Normative research will also assist in developing confidence intervals around particular scores to allow more accurate prediction of deviance.

An additional challenge for researchers is to explain why only some dyslexics have sensory processing deficits. A number of previous studies have attempted to explain why sensory deficits exist in only a sub-group of dyslexics. For example, some studies have proposed visual contrast sensitivity and motion detection deficits only exist in a sub-type of dyslexia with poor phonological decoding skills (Slaghuis & Ryan, 1999; Borsting et al., 1996). However, other studies have failed to find evidence for this relationship (e.g., Williams et al., 2003; Ridder, Borsting & Banton, 2001). Other studies suggest sensory deficits exist only in dyslexics with co-existing oral language disorder (Heath et al., 1999), while still others have argued the deficits observed are the result of inattention in dyslexics while performing psychophysical tasks (Roach et al., 2004; Stuart et al., 2001). This study investigated the alternative hypothesis that the definition of dyslexia used by this and previous investigations may result in individuals with environmental rather than neurological based (dyslexia) reading difficulties being included in dyslexic groups. In fact, previous research has demonstrated that ~50% of children who initially meet criteria for dyslexia began to read at average levels or above following intensive reading intervention (e.g., Vellutino et al., 1996). It was therefore predicted that only those children who made low growth in response to a school based remediation programme would have sensory processing deficits. This hypothesis was not supported by the results of the present study. However, it must be noted that the

intervention did not prove particularly effective for any child in the study (see Figure 30). This contrasts with the results of the structured intervention programme instituted and run by Vellutino et al., who found that only a small group of the most severely affected poor readers failed to respond to intervention. Therefore on the basis of the current data, growth in reading skills should not be totally discounted as a predictor of who does and does not have sensory processing deficits. Future research that implements a more structured and controlled intervention in children of approximately the same age and grade level would more effectively test this hypothesis.

An alternative hypothesis is that the presence of a sensory deficit represents a genetic risk factor for developing reading difficulties, but that a sensory processing deficit does not lead to reading difficulties on its own. The risk will only become manifest in combination with other risk factors, such as phonological impairments or an impoverished educational or home literacy environment (which can lead to reading difficulties on their own). This theory can explain the correlations that existed in the current study between the sensory processing and reading measures (i.e., individuals with sensory impairments tended to be more impaired on language and literacy tasks than those who did not have sensory impairments). It can also explain the findings in the current data that some individuals without apparent reading problems also have sensory impairments. That is, while an individual may be at risk, protective factors, such as intact phonological skills or appropriate reading instruction in early school years, may prevent development of reading difficulties. The current data do not permit investigation of this hypothesis. However, future investigations that investigate genetic factors and the prevalence of reading difficulties and sensory processing deficits in families may prove profitable.

5.13 Conclusion

In demonstrating that previous findings of relationships between sensory processing skills and reading can be replicated both externally and internally, the current study has added important new evidence for the reliability of these findings. The dyslexic group had significantly lower sensitivity across all of the sensory processing tasks, and sensitivity to the temporal variables 2 Hz FM and coherent motion could account for small, but significant portions of the variance in reading skills, even after accounting for the effects of IQ and vigilance. However, contrary to previous research, the current study found that the dyslexic group had a general rather than a specific temporal impairment in the auditory domain. Replicating this data and determining what leads to poor performance across a range of stimulus tasks will be an important avenue for future research. The current study also failed to support the prediction made by Vidyasagar (1999) that visual attention can explain the link between visual processing deficits and reading. Only one dyslexic participant who was impaired on the serial search task had a co-existing deficit in detecting coherent motion. The current study also demonstrated that although statistically significant differences were observed in the sensory processing thresholds of the dyslexic and control groups, the magnitude of these effects was typically small and substantial overlap existed between the sensory thresholds of the two groups. The deviance analysis revealed that only a small number of dyslexic participants had actual impairments on the auditory and visual tasks when compared to the control group mean; nor were impairments confined to the dyslexic group, as a number of control participants also had deviant thresholds on the sensory processing tasks. A major challenge for future research will be to explain why sensory deficits appear to exist in only a sub-group of individuals classified as dyslexic, and why some skilled readers also have similar deficits.

6.0 References

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