Investigating which processes influence reading fluency in dyslexic and non-dyslexic groups

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Abstract

This thesis reports an investigation of the component processes underlying reading fluency.

A current controversy in reading research is whether reading ability and development is determined solely by linguistic processes such as phonological (sound-based) skill, or whether it can also be influenced by non-linguistic processes such as visual processing of print, attention and general timing capacity. One way of addressing this problem is to investigate *naming speed*; the speed with which objects, colours, letters or digits can be named. Letter naming in particular represents a 'microcosm' of the processes required for fluent reading.

The experiments in this thesis systematically manipulate the letter naming process to investigate a) what determines naming-speed performance and b) which processes, when aberrant, cause slower naming in dyslexic readers. Results suggest that non-dyslexic readers are better able to process multiple letter items simultaneously than dyslexic readers. Further, we find evidence suggesting a strong role for phonological retrieval in determining naming latencies and contributing to the naming-speed deficit. We also identify a strong attentional component and a role for visual processing in naming speed which discriminates dyslexic and non-dyslexic reading groups. The results support models emphasising the multi-componential nature of reading fluency and suggest that naming deficits in dyslexia reflect processing difficulties in non-phonological, as well as phonological domains.

Ar gyfer fy nheulu

"Learning to read involves integrating a system for processing written language with one that already exists for processing spoken language."

(Snowling, 2000).

Declaration

This thesis has been composed by myself, and the research presented herein is my own. No portion of this work has been submitted for any other degree or professional qualification.

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CHAPTER 1

Introduction

1.0 Chapter overview

This chapter gives a brief introduction to the concepts of reading and dyslexia. We outline some of the challenges facing dyslexia researchers and suggest how *naming speed* tests might provide a window into the multi-componential nature of reading fluency. We end by outlining the main aims of the thesis.

1.1 Understanding reading and the cause(s) of reading difficulty

Unlike language acquisition, reading is not an evolved skill. The invention and spread of the alphabetic principle began as recently as c. 1700 BC (Healey, 1990), although logographic scripts pre-date this period. Biologically speaking, reading alphabetic scripts is not the product of specialised cortical centres (Wolf & Kennedy, 2003), nor can its behavioural development depend on mere exposure to print during development. The process of reading is largely parasitic on pre-existing linguistic structures, and at least some explicit instruction is required in order to master the skill. As well as representing an extension of the communicative act of speaking in visual form, reading represents an impressive display of the plasticity and adaptive capabilities of the human brain without the need to develop specialised centres.

Using linguistic knowledge in combination with sophisticated visual scanning and orthographic matching, the brain succeeds in converting visual symbols into meaningful information. Reading recruits processes from a number of different modalities; requiring a capacious attention span from the learner. Despite its unevolved origins and recruitment of multiple brain regions, perhaps the most astonishing aspect of reading is that when this process reaches an advanced state, the ‘skilled’ reader accomplishes the task quickly and fluently. This is the point at which reading is considered to have become *automatised*, or automatic. Reading therefore represents one of the most complex feats of the human brain, yet when mastered it is executed with considerable ease.

For some individuals, however, effortless and fluent reading is never fully achieved, which is perhaps not surprising given the demands of the task. What *is* surprising is that failure to acquire adequate literacy skills (reading and writing) can and often does occur independently of intelligence and general cognitive functioning. An estimated 7% of the population demonstrate poor performance in reading compared with age and reading-matched peers, whilst otherwise demonstrating a generally high IQ (Shaywitz, Shaywitz, Fletcher & Escobar, 1990). This cognitive profile is known as *developmental dyslexia*.

Ellis (1985) noted that the absence of specialised brain structures for reading implies that developmental dyslexia cannot be classified as a *reading disorder*. Rather, it involves malfunction of areas that have evolved for other purposes. This encapsulates one of the primary challenges facing dyslexia research: if reading is parasitic on multiple brain areas that have evolved for perceptual, cognitive, linguistic and motoric purposes, it becomes very difficult to determine the relative importance of these loaned brain structures to reading. Tracing the cause of the reading difficulty is consequently anything but straightforward.

1.2 What causes dyslexia?

Chapter 2 provides a review of the main causal theories associated with developmental dyslexia, and it becomes clear that a host of neurological, perceptual and cognitive skills have been causally implicated with the reading difficulty. As we shall see, the phonological deficit hypothesis is currently the most established theory, which locates the deficit in dyslexia in the consolidation and retrieval of phonological, or sound based codes (Brady & Shankweiler, 1991; Bradley & Bryant, 1978; Frith, 1985; Snowling, 1981; Snowling, 2000; Stanovich, 1988 Vellutino, 1979). Competing theories locate the cause of dyslexia in processing rapid auditory information (Tallal, 1980; Tallal et al., 1993), visual processing (e.g., Galaburda & Livingstone 1993; Stein & Walsh, 1997) and in automatising motoric (including articulatory) gestures (e.g., Nicolson & Fawcett, 1990). Each hypothesis is of course associated with a neurological site, but proponents of each theory vary in terms of their emphasis on neurological, perceptual or cognitive descriptions of the deficit.

The recent success of the phonological deficit hypothesis has perhaps advocated an approach to dyslexia research that encourages researchers to identify a single causal deficit. Alternatives to this approach typically include *dual-route* models, in which a phonological reading route operates alongside a lexical route, which specialises in identifying words as a whole (e.g., Coltheart, Rastle, Perry, Langdon, & Zeigler, 2001). Employing a similar conceptualisation of reading mechanisms, Wolf and Bowers (1999) propose a *double-deficit* hypothesis of dyslexia, in which phonology comprises a potential source of breakdown in the reading process. Such a deficit incurs difficulty in decoding written words. An alternative source of difficulty, demonstrated by dyslexic readers is termed the *naming-speed* deficit: When tested on a Rapid Automatised Naming (RAN) test (e.g., Denckla & Rudel, 1979), which requires naming of serially presented familiar, lexicalised items such as objects, colours, digits and letters, dyslexic readers generally yield longer latencies than average or skilled readers.

Given the status of the naming-speed deficit as statistically independent from phonology (although it does of course comprise an influential phonological component in retrieving the label of each item), naming speed is proposed, and indeed there is empirical evidence to suggest that it contributes independent variance to reading fluency (Bowers, 1993, 1995; Bowers & Swanson, 1991; deJong & van der Leij, 1999; Kirby, Parrilla, & Pfeiffer, 2003 Young & Bowers, 1995). As such, sub types of dyslexia are possible, in which individuals may exhibit single-deficit phonological or naming speed deficits, or both. Future research examining individuals with dyslexia across neurological, perceptual and cognitive domains may fail to find evidence of two (or more) independent substrates for reading. Instead, a common neurological site, such as the models proposed by proponents of cerebellar and domain-general magnocellular deficits (e.g., Nicolson & Fawcett, 1990; Stein & Walsh, 1997; see also Chapter 2) may be implicated for factors that appear to be cognitively independent. The model outlined by Wolf and Bowers (1999) provides, however, a starting point from which to examine *extra*-phonological difficulties in dyslexia at the cognitive level of explanation.

1.3 How can naming speed help us to understand dyslexia?

Wolf and Bowers (1999) propose that the functional independence of phonology and naming speed relies on the multi-componential nature of naming speed. In addition to a phonological component, it is suggested that attentional and/or visual processing play an important primary role in determining the speed with which participants name a series of items. As such, naming speed may represent the cognitive manifestation of the attentional, visual and domain-general causal deficit hypotheses that currently rival the phonological explanation.

As we shall see in Chapter 2, there is a substantial literature suggesting the independence of naming speed from phonological skill. Chapter 3 points out, however, that very little work to date uses experimental methods in order to pinpoint which component processes in naming speed influence performance on these tasks.

1.4 Aims of the thesis

The thesis addresses this gap in the current literature. We examine the influential components of naming-speed performance on the RAN-Letters task using a series of experimental designs. The main aim of this thesis is to investigate the evidence for the involvement of *extra*-phonological processes (attentional and visual factors) in naming speed in order to a) assess their importance to naming speed and reading fluency in general and b) investigate their ability to explain the naming-speed deficit and fluency impairment in dyslexia. This thesis therefore tests the validity of the model set out by Wolf and Bowers (1999), and our findings will help to elucidate the low-level processes involved in reading fluency.

In order to accomplish our aims, we compare reaction times (henceforth referred to as RTs) across dyslexic and non-dyslexic reading groups on a series of RAN task manipulations. Chapter 4 begins this investigation by systematically isolating different behavioural requirements for successful naming on the original RAN task. Specifically, we ask whether the complexity inherent in the original RAN, involving the necessity of sequencing multiple items, is a critical determiner of RAN speeds for dyslexic and non-dyslexic readers. Chapters 5 and 6 compare reading groups on versions of RAN that tax either visual or phonological components of the task. This represents our attempts to separate these domains in order to assess their influence on RAN. Chapter 7 is designed to accomplish a similar aim, but in order to gain a finer grained understanding of RAN processes, including the relationship between eye-movements and articulation of the phonological label, we use eyetracking methodology. Chapter 8 examines a potential locus for a specific visual influence on RAN.

We will see that both phonological and visual domains influence naming speeds for both dyslexic and non-dyslexic readers. These experiments suggest that extra-phonological domains not only influence naming speeds in general, but contribute to the naming-speed deficit characteristic of dyslexia. Our findings begin to elucidate the low-level component processes involved reading fluency.

CHAPTER 2

Literature Review

2.0 Chapter Overview

The chapter begins by outlining areas of disagreement in dyslexia research. We then consider the main causal hypotheses of developmental dyslexia. Sections including descriptive, empirical and evaluative summaries are dedicated to each causal hypothesis in turn. This is followed by a review of the double deficit hypothesis. The chapter ends by considering the evidence for a naming-speed deficit in dyslexia, which is independent of phonological skill.

2.1 Why the disagreement?

When discussing the causes of dyslexia, it is necessary to consider all potential levels of explanation. Whilst the behavioural expression or symptom of dyslexia is a difficulty in learning to read, the underlying causes have been located at cognitive, biological and genetic levels of explanation. Indeed, an optimal model would demonstrate how dyslexia is expressed at each level.

A prolific amount of research has been and continues to be conducted on the genetic, biological, cognitive and behavioural aspects of dyslexia, and the majority of researchers are demonstrating a commitment to explain dyslexia on different levels of functioning. Despite this, we are currently far from a unified, coherent account of the causes of the reading impairment. Instead, it is a topic that remains widely disputed, and individual research teams tend to focus on isolated features of the reading deficit. It would appear that the primary reasons for this segregation are twofold: There is widespread disagreement in the field as to *how many* causes underpin dyslexia, and whether or not the deficit is *language specific*. The following sections will outline the major causal theories of dyslexia with reference to these key disagreements in the research field.

2.2 The phonological deficit hypothesis

In his seminal publication *Dyslexia: Research and Theory*, Vellutino (1979) outlined the hypothesis that reading-specific deficits (which had thus far been outlined as perceptual impairments) were in fact consistent with a cognitive model, comprised of impaired verbal encoding. Owing to cases of highly articulate dyslexic individuals, this original hypothesis shortly afterwards became restricted to encompass only phonological ability. However, this work united dyslexia researchers, and over the next two decades inspired research positing cognitive linguistic deficits as the sole putative cause of dyslexia.

The phonological deficit hypothesis acknowledges the existence of genetic and neurological (left perisylvian abnormality; Larsen, Hoien, Lundberg, & Odegaard, 1990; Snowling, 2000) features of dyslexia, but proposes a straightforward causal link between the cognitive impairment (phonological processing) and the behavioural outcome (difficulty learning to read) (Ramus, 2003). Within this explanatory framework, dyslexia is caused by a language-specific deficit within the phonological system, caused by difficulty in processing the speech stream (Brady & Shankweiler, 1991; Bradley & Bryant, 1978; Frith, 1985; Snowling, 1981; Snowling, 2000; Stanovich, 1988 Vellutino, 1979). As a result, phonological representations of speech sounds are degraded and ill-specified (Elbro, 1996; Hulme & Snowling, 1992; Snowling, 2000). Such impaired phonological representations are manifest in tasks requiring different facets of phonological processing.

Studies have demonstrated that compared to normally developing readers, dyslexic children are impaired on tasks involving non-word repetition (Elbro, Borstrom, & Petersen, 1998; Snowling, 1981; Snowling, Stackhouse, & Rack, 1986), phonological learning (Aguiar, & Brady, 1991; Wimmer, Mayringer, & Landerl, 1998) phonemic awareness (e.g. Bradley, & Bryant, 1978; Griffiths, & Snowling, 2002; Morris et al., 1998), picture naming (Snowling, van Wagtendonk, & Stafford, 1988) and verbal short term memory (Griffiths & Snowling, 2002; Nelson &

Warrington, 1980; Rack, 1985). Recent methodological developments have also demonstrated on-line phonological rhyme processing deficits (Desroches, Joanisse, & Robertson, 2006). Furthermore, phonological deficits persist into adulthood, even in adults who have learned to compensate somewhat for their reading difficulties by using other cognitive strengths (Bruck, 1992; Campbell & Butterworth, 1985; Fawcett & Nicolson, 1995; Funnell & Davidson, 1989; Howard & Best, 1996; Shaywitz et al., 1999).

Within the phonological deficit hypothesis, there remains some controversy as to the precise sub-component of speech processing that is impaired (Szenkovits & Ramus, 2005): whether, for example, it represents impaired phonological 'input' processes (Bonte & Blomert, 2004; Mody Studdert-Kennedy, & Brady, 1997; Ramus, 2001; Serniclaes, Van Heghe, Mousty, Carre, & Sprenger, 2004) such as auditory processing (Farmer & Klein, 1995; Tallal, 1980) or categorical perception (Adlard & Hazan, 1998; Blomert & Mitterer, 2004; Mody et al., 1997; Rosen & Manganari, 2001), or whether phonological output processes are impaired (Elbro, 1996; McCrory, Mechelli, Frith, & Price, 2005; Snowling, 2000). Despite these disagreements, the phonological deficit hypothesis is united in its claim that phonological deficits (in any form) are the only cause of dyslexia, and it is even suggested that the manifestation of the specific phonological deficit might be individually determined (Szenvokits & Ramus, 2005).

2.2.1 How does impaired phonology result in a reading deficit?

In the language system, the phonological domain maps the speech sounds of language to units of meaning (Pinker, 1994). Written language makes an additional demand, that printed letters (graphemes) and words (orthography) must be translated into articulated output, which requires a more conscious level of phonological manipulation (Lundberg & Hoien, 2001). A translation from visual symbols to units of sound at the letter level is known as grapheme-to-phoneme correspondence, and acquiring this alphabetic principle allows the reader to demonstrate flexibility when reading new or complex words (Jorm & Share, 1983; Share, 1995). If the reader is familiar with the visual word forms “hat” and “pit”, for example, knowledge of the phonemes /h/ /a/ /t/ /p/ /i/ /t/ allows them to recombine the associated graphemes in order to recognise and articulate other words with similar phoneme combinations such as “pat” and “hit”.

Grapheme-to-phoneme mapping in opaque orthographies such as English is rarely straightforward, however. In Chapter 1, reading was described as a culturally defined parasitic artefact of language evolution, and ease of language production and comprehension is unfortunately at odds with a one-to-one mapping of graphemes to phonemes. In the phenomenon of coarticulation, adjacent phonemes within a word influence each others’ articulation. For example the vowel /i/ in the word ‘pit’ is sharp, but in the word ‘pin’ it acquires the nasal properties of the subsequent consonant. As a result, phonemes associated with individual graphemes vary depending on adjacent graphemes in the word. Coarticulation facilitates speed of articulation and comprises an integral feature of the lexical item, aiding comprehension against background noise. In terms of reading, however, the appropriate phoneme must be chosen to match the grapheme in a given context. In order to achieve this, the reader must be in possession of a bank of highly developed phonological representations.

From a connectionist perspective (Harm & Seidenberg, 1999; Plaut, McClelland, Seidenberg, & Patterson, 1996; Seidenberg & McClelland, 1989), a reader with good phonological representations will be able to establish a sophisticated web of connections between orthography and phonology through practice in different contexts (Snowling, 2000). The dyslexic reader, on the other hand, will have only very coarse mapping of how the phonology relates to larger units such as whole words or syllables. Frith (1985) describes this process as “arrest at the logographic stage” of reading development, implying a compensatory over-reliance on visual word form recognition. The absence of grapheme-to-phoneme awareness implies that whilst reading highly familiar words using visual strategies may not pose a great problem, dyslexic readers lack the flexibility and tools to decode complex novel words. An overwhelming amount of evidence exists suggesting that this is the case.

Dyslexic readers consistently demonstrate a profound inability to decode novel or nonsense words compared with normally developing readers (e.g. Griffiths & Snowling, 2002; Snowling, 1981; Snowling, Goulandris, & Defty, 1996).

2.2.2 Evaluating the phonological deficit hypothesis

A substantial amount of evidence has accumulated, identifying a causal link between phonological awareness and reading ability (see Goswami & Bryant, 1990 for a review), and general phonological ability is a reliable predictor of success in learning to read (Bradley & Bryant, 1997; Elbro et al., 1998; Stanovich, Cunningham, & Cramer, 1984). Training in phonemic awareness can also improve the development of reading (Bradley & Bryant, 1983; Ehri, Nunes, Stahl, & Willows, 2001). Indeed, it is argued that dyslexia should be operationally defined by the existence of a phonological deficit (Stanovich, 1986).

Whilst it is clear that dyslexia is characterised by impaired ability to manipulate phonological representations, two broad assumptions of the hypothesis are subject to criticism: specifically, the claim that phonological deficits are a direct cause of reading disability, and consideration of phonology as the *only* cause of reading disability.

2.2.2.1 A direct causal link between phonology and dyslexia?

Despite the demonstrable relationship between phonological processing and reading ability, some researchers claim that no concrete evidence of a *direct causal* link currently exists. In a recent review article, Castles and Coltheart (2004) argued that no study to date has demonstrated sufficient experimental control to conclude that phonology *per se* influences reading, and not an unspecified third variable. According to the authors, phonology is characterised as a proximal cause, or symptom, of a visual deficit with concurrent deficits in orthographic processing and phonology. A similar rationale underpins claims that phonological impairment reflects underlying auditory, motor deficits in reading, as well as other non-linguistic skills (Nicolson, & Fawcett, 1990; Fawcett, Nicolson, & Dean, 1996; Tallal, 1980;

Tallal et al., 1993; Werker & Tees, 1987). In response to these criticisms, advocates of the phonological hypothesis counter that mediation of phonological awareness by other variables (such as letter-sound knowledge) does nothing to diminish the causal role of phonology in reading ability; it merely provides a more detailed understanding of the different influential component structures (Hulme, Snowling, Caravolas, & Carroll, 2005). Furthermore, several meta-analytical studies demonstrate that whilst phonological deficits occur in most of the sample, sensorimotor difficulties occur in only a sub-set (Ramus et al., 2003; White et al., 2006), suggesting that phonology is not mediated by a sensory impairment.

Despite these ripostes, weakness of argument and methodology in these studies compromise the integrity of their defence. For example, in support of the phonological hypothesis, Hulme et al. (2005) re-conceptualise moderator and mediator variables as being equally culpable in terms of causality, thus reclaiming phonology as a causal factor in dyslexia. In so doing, the authors fail to distinguish between factors that are arguably cognitive causes of *reading disability* (such as phonological impairment, for example) but are not necessarily direct, underlying causes of *dyslexia*. In essence, Hulme et al. blur behavioural and cognitive levels of explanation, using definitions of ‘symptom’ and ‘cause’ interchangeably.

2.2.2.2 Phonology as the only cause of dyslexia?

The characteristics of dyslexia are notoriously heterogeneous (e.g. Hynd & Cohen, 1983), which makes a single causal model of dyslexia inherently dubious. A single causal model at a sensory level has the explanatory advantage that a range of symptoms can ensue, causing apparent sub-types of the reading deficit. The phonological deficit hypothesis, however, is at a logical disadvantage in that the causal relationship projects from a higher, cognitive level, apparently allowing for little variation within dyslexic reading groups. However, a connectionist approach to reading (Harm & Seidenberg, 1999; Plaut, McClelland, Seidenberg, & Patterson, 1996; Seidenberg & McClelland, 1989) can account for the variance between individuals without conceding to a multi-causal definition: individual variance in reading disability reflects the degree to which phonological processing is impaired in conjunction with the individual strengths (e.g. contextual, semantic) that are brought to bear in order to compensate for the difficulty. This rationale is the basis for the *severity hypothesis*, which views individual variance as a function of the severity of the phonological deficit (Griffiths & Snowling, 2002; Snowling, Goulandris, & Stackhouse, 1994).

A hypothesis stemming from this theoretical stance is that all reading difficulties, no matter how diverse, reflect core phonological processing deficits. This position is at odds with more traditional models of reading, however, that comprise two independent reading routes. Coltheart et al.'s (2001) dual route cascaded model, for example, consists of a lexical route, which relies on visual recognition of the word's orthography. A second phonological route operates a sub-lexical processing mechanism, decoding words using a grapheme-to-phoneme strategy. According to this framework, *phonological dyslexia* occurs as a result of damage to the phonological reading route. Damage to the lexical route incurs *surface dyslexia*; resulting in an impaired ability to recognise words by their orthography. The latter type of dyslexia is therefore independent of a phonological deficit. Indeed, the model predicts that the reading system becomes *more* dependent on phonology to compensate for poor sight word recognition (Coltheart et al., 2001). Coltheart's sub-typing of dyslexic symptoms is analogous to the *dysphonetic* and *dyseidetic* types formerly identified by Boder (1973).

The literature yields ambiguous results in support of both connectionist and dual route reading models. A number of studies demonstrate that a phonological deficit is prevalent even in dyslexic readers with impaired irregular word reading, traditionally associated with surface dyslexia (Bailey, Manis, Pedersen, & Seidenberg, 2004; Castles et al., 1999; Springer-Charolles et al., 2000; Stanovich et al., 1997). In line with a dual route dichotomy, however, other studies suggest that whereas phonological dyslexics show impaired analysis of phonological structures and pseudo-words, surface dyslexics perform similarly to age-matched controls (Manis et al., 1996; Curtis, Manis, & Seidenberg, 2001). In general, it is found that phonological impairment implies pseudo-word reading difficulty, but it can also prevent acquisition of lexical knowledge (Share, 1995, 1999). It is therefore possible that a severe phonological deficit could result in some difficulty in recognising irregularly spelled ('exception') words. Both dual route and connectionist reading models concord, however, that a mild phonological deficit should not predict exception word ability (e.g. Harm & Seidenberg, 1999). These findings suggest that exception word reading ability might be a function of one (or even several) non-phonological processes (Valdois, Bosse, & Tainturier, 2004). Theories and evidence supporting a multi-causal explanation of dyslexia will be elaborated on in subsequent sections.

2.3 Sensorimotor causal hypotheses

The broad heterogeneity of dyslexic characteristics has led to a burgeoning literature on alternative theories to the phonological deficit hypothesis. These theories typically attribute a single- or multi-deficit causal explanation of dyslexia, in which phonological impairment is symptomatic of lower-level abnormalities. Causal theories that focus on low-level cortical and sub-cortical brain functioning can explain the broad range of symptoms associated with dyslexia because an early deficit can cascade to potentially all subsequent cognitive difficulties associated with the reading process. This section will review the main theories advocating a sensorimotor causal basis of dyslexia.

2.3.1 The Rapid Auditory Processing theory

The rapid auditory processing theory demotes phonological deficits from being the primary cause of the reading disorder to being symptomatic of an underlying auditory deficit. That is, phonological deficits are the direct result of impaired ability to perceive short or rapidly varying sounds (Tallal, 1980; Tallal et al., 1993). Support for this theory comes from studies demonstrating dyslexic readers' poorer performance on auditory tasks, such as temporal order judgements; the ability to identify items heard and judge which came first (e.g., Kinsbourne, Rufo, Gamzu, Palmer, Berliner, 1991; McAnally & Stein, 1997; Reed, 1989; Nagarajan et al., 1999;

Tallal, 1980); discrimination of stimulus sequences (Bryden, 1972; McGivern, Berka, Languis, & Chapman, 1991; Zurif & Carson, 1970), and impaired temporal frequency discrimination (Ahissar, Protopapas, Reid, & Merzenich, 2000; McAnally & Stein, 1997). Furthermore, dyslexic readers show evidence of impaired neuropsychological responses to various auditory stimuli (Kujala et al., 2000; McAnally & Stein, 1996; Nagarajan et al., 1999; Ruff, Cardebat, Marie, Demonet, 2002; Temple et al., 2000).

These findings suggest a basic low-level auditory impairment in dyslexia, and its effect on reading ability is to impede the development of adequate phonological representations. On a behavioural level, impaired ability to process short sounds and fast transitions between sounds should impair the ability to discriminate similar speech sounds, or morphemes. When exposed to varying clarity of the sounds /ba/ and /pa/ (both consonants constituting bilabial fricatives) in categorical perception tasks, for example, average readers demonstrate a strict cut-off-point at which either sound is heard, but dyslexic readers' perception of either phoneme follows a more shallow function (Adlard & Hazan, 1998; Manis et al., 1997; Mody, Studdert-Kennedy, & Brady, 1997; Sernicles et al., 2001). In sum, therefore, the rapid temporal auditory deficit demonstrated by dyslexics is the direct cause of phonological deficits and the ensuing reading disability. Advocates of the theory are mostly non-specific concerning the deficit's biological origin, but a causal role for magnocells has been proposed, which will be outlined in section 2.3.4.

2.3.2 Visual Theories

Although the phonological deficit hypothesis is the current most established causal theory of dyslexia, an initial hypothesis linked reading difficulty with visual problems. In the late 19th and early 20th century, case studies of children with "word-blindness" were reported (Morgan, 1896), and Orton (1925) described the difficulties exhibited by such children as *strephosymbolia* (twisted signs). Orton claimed that unstable visual representations of letters and letter order within and between words caused the reading disability. This view enjoyed something of a renaissance in the 1990s, and is the basic premise of the visual magnocellular deficit hypothesis.

Early research by Lovegrove suggested that visual difficulties stem from impaired transient visual pathways in the Lateral Geniculate Nucleus (LGN) (e.g., Lovegrove, Bowling, Badcock, & Blackwood, 1980; Slaghuis & Lovegrove, 1984). The LGN comprises two pathways, which run in parallel and to a large degree remain separate in their projection to the primary cortex (V1). Parvocells process information of form and colour, which is not demonstrably impaired in dyslexia (e.g. Lovegrove et al., 1980). Magnocells detect transient movement information in the visual field (Galaburda & Livingstone 1993).

The transient visual deficits described by Lovegrove have since been attributed to the magnocellular pathway (see Stein & Walsh, 1997). A number of psychophysical studies demonstrate impaired performance in dyslexic compared with non-dyslexic readers on measures of magnocellular processing, such as sensitivity to dynamic visual stimuli (Cornelissen, Richardson, Mason, & Stein, 1995; Lovegrove et al., 1980; Lovegrove, Martin, & Slaghuis, 1986; Livingstone, Rosen, Drislane, & Galaburda, 1991; Mason, Cornelissen, Fowler, & Stein, 1993), ability to detect coherent motion in random dot kinematograms (Cornelissen et al., 1995; Cornelissen, Hansen, Gilchrist, Cormack, Essex, & Franklish, 1998; Pammer & Wheatley, 2001), and ability to perceive global movement at short interstimulus intervals on a Ternus illusion task (Cestnick & Coltheart, 1999; Slaghuis, Twell, & Kingston, 1996).

Stein and Walsh (1997) and Stein and Talcott (1999) proposed that magnocellular irregularity causes unstable fixations during reading, leading to inaccurate processing of orthographic information. However, findings relating magnocellular deficits and dyslexia have not been consistently replicated, nor are they found on multiple task comparisons (Evans, Drasdo, & Richards, 1994; Walther-Muller, 1995). Furthermore, several studies demonstrate an important role for visual attention but find no evidence of an additional magnocellular deficit (Iles, Walsh, & Richardson, 2000; Roach & Hogben, 2004; Steinman, Steinman, & Garzia, 1996; see Ramus

(2003) and Skottun (2005) for reviews of the evidence relating to magnocellular deficits in dyslexia).

To account for these contradictory findings, the magnocellular hypothesis of developmental dyslexia has been substantially revised to include a stronger role for visual attention (e.g., Pammer & Vidyasagar, 2005). From the primary cortex, two visual streams are known to project information to other cortical areas. The dorsal stream (dominated by magno-inputs) projects to V2 and to V5 and the parietal cortex. Information carried by this stream is considered critical in the pre-attentive control of spatial selection. In contrast, the parvo-dominated ventral stream projects to areas V2, V3, V4 and the inferotemporal cortex, and operates a more detailed analysis of form, colour and texture (Vidyasagar, 1999). Recent research proposes that dyslexic visual deficits may be located in the dorsal stream (Pammer & Vidyasagar, 2005).

Vidyasagar (1999) and Pammer and Vidyasagar (2005) suggest that different processing styles exhibited by dorsal and ventral visual pathways reduce the computational load on the visual system that might arise if both pathways operated simultaneously on the same visual input features. The dorsal stream acts as an ‘attentional spotlight’, guiding visual attention to salient components of the visual stimulus. A decision is made concerning regions of interest which is followed by more detailed (ventral) processing of that region (Pammer & Vidyasagar, 2005). In reading, the dorsal stream allocates attention to appropriate areas of text, providing sufficient feedback to the ventral stream to allow fine-grained analysis of letters (Pammer & Vidyasagar, 2005). Empirical findings that dorsal functioning is critical in the pre-lexical stages of word processing support this account (Mayall, Humphreys, Mechelli, Olson, & Price, 2001). A dorsal stream *deficit* might therefore impede smooth attentional focus on orthographic items, disrupting the visual discrimination of letters that is accomplished by the ventral stream (Pammer & Vidyasagar, 2005).

Pammer, Lavis, and Cornelissen (2004a) investigated whether dorsal stream functioning influences reading ability via letter-position encoding. Letter-position encoding refers to readers' sensitivity to the relative locations of orthographic items within a string; less skilled readers are more inaccurate in judging item position compared with highly skilled readers (e.g. Mason, 1980). One measure of letter-position encoding is the *symbols* task, in which symbol strings are briefly presented to the participant; the participant memorises the position of each item in the string and then selects the correct string from a forced choice of two alternatives. Using letter-like symbols eliminates lexical influences, yielding a measure of how well the relative positions of items are visually encoded. Child dyslexic readers give fewer correct responses in this task than non-dyslexic readers (Pammer, Lavis, Hansen, & Cornelissen (2004b). Furthermore, performance on the task significantly predicts word recognition ability in adults (Pammer, Lavis, Cooper, Hansen, & Cornelissen, 2005). Pammer et al. (2004a) investigated the relationship between letter position encoding and dorsal functioning. The authors found that although both measures predicted reading skill, they were not related to each other. Pammer et al. suggest a division of labour for spatial processing in reading, such that dorsal functioning operates a coarse, peripheral analysis of text independently of the detailed, more centralised spatial analysis provided by ventral processes that underpins letter-position encoding. Jones, Branigan, and Kelly (in press) suggest that RAN and word reading performance involve a combination of both dorsal and ventral processes (see Chapter 8 and Appendix C).

Letter position encoding is therefore an influential factor in reading (Pammer et al., 2004a, b), which may rely on the interaction between dorsal and ventral processes. This hypothesis suggests that the magno-dominated dorsal stream is an important influence on reading ability, but crucially locates the source of this influence on later visual processing stages than magnocellular projections to V1. Indeed, a number of studies demonstrate an important role for visual attention in the absence of an additional magnocellular deficit (Hogben, 1997; Iles, Walsh, & Richardson, 2000; Roach & Hogben, 2004; Steinman, Steinman & Garzia, 1996). As a result, it appears that deficits in visual attention *can* occur as a result of magnocellular deficits, but they are not a prerequisite for such an attention deficit.

Although a role for visual attention is specified in models of single word reading and eye movement control (Behrmann, Moscovitch, & Mozer, 1991; Laberge & Samuels, 1974; Laberge & Brown, 1989), most theories of reading are not specific about the attention processes involved in visually analysing letter strings, and assume that visual processing is a peripheral aspect of reading (i.e. it is not integral to the reading process itself) (Coltheart, Curtis, Atkins, & Haller, 1993; Coltheart, et al., 2001; Harm & Seidenberg, 1999; Plaut, McClelland, Seidenberg, & Patterson, 1996; Seidenberg & McClelland, 1989). An exception to this is the connectionist multi-trace model of polysyllabic word reading (Ans, Carbonel, & Valdois, 1998), which distinguishes between global versus analytic reading based on the breadth of the visual attention window (VAW). In short, global reading mode extends the attention span across the whole letter sequence, and all the phonological output is generated at once. Analytic processing requires a narrowing of the VAW; phonological output corresponding to each attentional sequence. In general, familiar words are computed via a global VAW, and encounters with pseudo-words are initially global but re-coded in an analytic processing style when global processing fails. Ans et al. (1998) demonstrated that a reduction in VAW size prevents global processing, impairing irregular word reading by increasing the number of regularisation errors. The model is silent with regards to phonological deficits in reading, however, and visual attention is thought to comprise only a subset of deficits in dyslexia (Bosse, Taintuer, & Valdois, 2006).

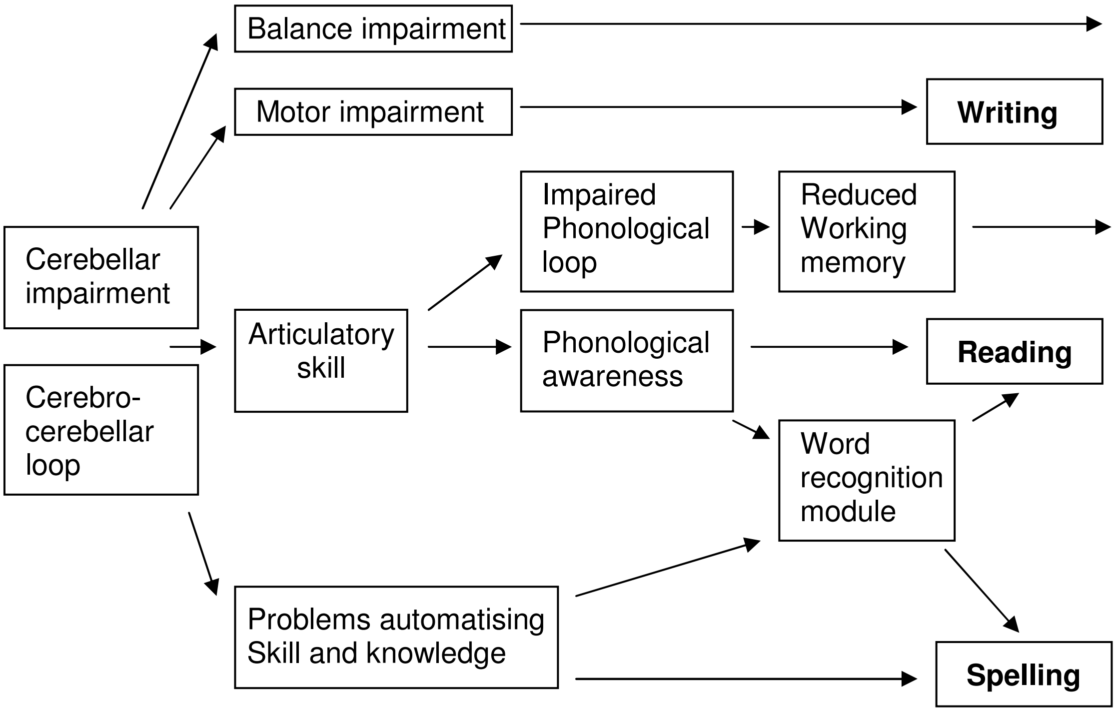
2.3.3 The Cerebellar deficit hypothesis

Evidence of sensory deficit theories in the auditory and visual domain perhaps makes intuitive sense, given that reading requires the integration of visual and sound information. However, a more recent theory provides evidence to suggest that deficits in learning *motoric* skill also have serious consequences for reading development. Nicolson and Fawcett (1990) demonstrated that a group of dyslexic children were impaired on a battery test of motor balance compared with a group of chronological age controls. Selected as representative of a non-linguistic, gross motor skill, this group discrepancy in relation to balance questioned the explanatory power of the phonological deficit hypothesis in accounting for the range of diverse characteristics typical of dyslexia. Subsequent studies comparing cognitive profiles of dyslexic children using tests related and unrelated to literacy have added credence to the validity of this enquiry, demonstrating pervasive deficits across information processing speed, memory, motor skill and balance (Nicolson & Fawcett, 1994a, b).

The cerebellar deficit hypothesis has emerged in order to explain this range of characteristics, by means of reconceptualising the cause of dyslexia to a biological site (the cerebellum). In so doing, the cerebellar deficit hypothesis acknowledges the prevalence of the phonological deficit in dyslexia, yet its status is viewed as symptomatic, or secondary to the primary neurological deficit. By locating the primary deficit at the cerebellum, the theory can account for a number of other symptoms in addition to the phonological deficit, such as motor, balance and automatising deficits. Thus, all demonstrable symptoms are traceable to one biological origin.

The cerebellum comprises half of all neurons in the brain, and is implicated in a number of motor tasks (Eccles, 1967; Holmes, 1917; Ito, 1984; Stein & Glickstein, 1992). The main premise of the cerebellar deficit hypothesis is that a cerebellar impairment affects the ability to automatise skills, with concomitant effects on literacy via different processing stages (Nicolson, Fawcett, & Dean, 2001). Figure 1 illustrates how these early deficits affect reading ability. One effect of cerebellar abnormality might involve a delay in babbling and talking, which affects the rate at which these skills are learned. As a result, the skills are less automatised and result in a lack of fluency when processing and retrieving familiar words. Furthermore, impaired articulatory representations arising from the cerebellar deficit can have direct implications for sensitivity to onsets, rime and other facets of phonological awareness. Indirect effects of this deficit include limited allocation of attentional resources to articulatory tasks, leading to an indirect impairment of phonological working memory (Baddeley et al., 1975). In addition to phonological deficits affecting reading and spelling, the cerebellar deficit also explains impaired dexterity in writing via motor skill deficits.

Figure 1: Cerebellar dysfunction, cascaded multi modal deficits and their effects on literacy (Based on Nicolson, Fawcett, & Dean, 2001; p. 510).



Evidence for a cerebellar cause of dyslexia comes from studies demonstrating similarities in symptoms of patients with acute cerebellar damage and dyslexia. Ivry and Keele (1989) showed that cerebellar patients found it difficult to estimate time judgements, yet were not impaired in estimating the volume of a stimulus, suggesting a deficit in processing temporal information. This effect was replicated in a group of dyslexic readers (Nicolson et al., 1995), and studies show that dyslexic children are impaired on a number of cerebellar tests compared with chronological age and reading-matched controls (Fawcett et al., 1996; Fawcett & Nicolson, 1999).

Direct measures of cerebellar impairment also yield reading group differences. Nicolson and Fawcett (1999) conducted a PET study, in which groups of dyslexic and control readers were taught sequences of button presses. PET scans revealed that in the control group, high levels of cerebellar activation was found in response to automatised and novel button press sequences. In contrast, the dyslexic group demonstrated significantly less cerebellar activation in the right hemisphere relative to controls in response to both automatised and novel sequences. The non-linguistic nature of this task demonstrates not only that there was clear, direct evidence of under-activation in the cerebellum, but also that the effect was not specific to language processing.

The cerebellar theory is a parsimonious yet comprehensive account of how the varied behavioural manifestations of dyslexia might arise from one biological deficit. As such, evaluation of the hypothesis, particularly from neuropsychologists and neurologists, frequently acknowledge the advantages of such a paradigm shift in tackling the problem of dyslexia, yet suggest different primary loci for the deficit. In response to Nicolson et al. (2001), Ivry and Justus (2001) applaud the cerebellar model of dyslexia in their conception of articulation as a skilled motor process linking an ostensibly linguistic reading deficit with a cerebellar (primarily motor) cause.

Although equally supportive of the sensorimotor model, Zeffiro and Eden (2001) question a direct role for the cerebellum in dyslexia, citing a dissociation between symptoms traditionally associated with cerebellar deficit and dyslexia. Specifically, dyslexic readers were found to lack the gross manifestations of a cerebellar deficit, whilst cerebellar patients often retained the ability to read fluently. The authors suggest either microscopic cerebellar impairments in dyslexia, or more probably, that the apparent cerebellar impairment itself is secondary to a primary deficit within the same neural circuitry. The cerebellum is part of a system including thalamic nuclei, neorcortical regions, pontine, and inferior olivary nuclei, and the function of each is mutually dependent on the other. A deficit in any of these regions would therefore affect cerebellar function, thus potentially mimicking a primary cerebellar deficit.

As an example, the authors refer to abnormalities in smooth visual pursuit in dyslexia. Cerebellar deficits are implicated in impaired smooth pursuit, but a similar deficit could be caused by abnormality in the visual input channel manipulated by the extrastriate cortex, affecting sensorimotor integration. As such, the demonstrably impaired smooth pursuit in dyslexia might be caused by inadequate information on movement of the visual background relayed to the cerebellum (Eden et al., 1994). Rather than locate the cause of dyslexia in the cerebellum, therefore, the authors refer to evidence favouring perisylvian neocortical regions as the primary causal region, which both receive information from and connect to the cerebellum (Eden & Zeffiro, 1998; Klingberg et al., 2000).

In response to these comments, Nicolson et al. (2001) refer to evidence of primary cerebellar impairment in dyslexic readers. Furthermore, the role of the cerebellum is viewed as crucial in the developmental stages of speech perception and resulting consolidation of phonological representations, which later become less dependent on the cerebellum, being instead located in the superior temporal (Hickok & Poeppel, 2000) or inferior parietal (Jonides et al., 1998) cortices. As a result, accounts of cerebellar damage in the absence of acquired dyslexia (Ivry & Gopal, 1992; Ackermann et al., 1997) do little to invalidate the cerebellar hypothesis, since the likelihood is that a strong role for the cerebellum is no longer required and phonological representations have already been established. Nicolson et al. (2001) acknowledge the importance of investigating neighbouring cortical regions of the cerebellum perhaps identifying different sub-types of dyslexia, based on different cerebellar regions or other implicated structures. Furthermore, Nicolson and Fawcett (2007) suggest that affected circuits can be tested empirically in order to separate potential confounding influences of other systems from cerebellar abnormalities.

2.3.4 The Magnocellular Hypothesis

Thus far, we have reviewed evidence of auditory, visual and motor deficits individually, reflecting their historical emergence. However, Stein and Walsh (1997) propose a unifying theory to account for evidence of deficits across different modalities. Working from the premise that magnocellular dysfunction causes visual deficits in dyslexia, the magnocellular deficit hypothesis is extended to include auditory, tactile, and as a result, phonological symptoms of dyslexia.

Post-mortem studies show that although auditory magnocellular neurons do not comprise a separate system, such as that demonstrated in the visual system, magnocellular regions of the thalamus (the medial geniculate nucleus) are disordered in dyslexic brains (Galaburda, Menard, & Rosen, 1994; Livingstone et al., 1991). Trussell (1998) demonstrated that auditory magnocells play a role in tracking rapid frequency and amplitude changes in acoustic signals, and Stoodley, Talcott, Carter, Witton, and Stein (2000) suggest magnocellular involvement in vibrotactile sensitivity.

However, as reviewed in previous sections, not all researchers agree with a magnocellular account of visual deficits in dyslexia (e.g., Bosse et al., 2006). Furthermore, Stein, Talcott and Witton's (2001) argument that magnocells in the cerebellum *cause* the motor and automatisation deficits has been refuted by Nicolson and Fawcett (2001). The authors indicate that even the magnocellular deficit hypothesis is not comprehensive enough to account for some symptoms of dyslexia, such as impaired time estimation and lowered muscle tone.

2.3.5 Can sensorimotor deficits cause dyslexia?

The appeal of sensory deficit hypotheses is that they provide a tangible neurological cause of dyslexia, with impairments cascading to the perceptual and/or cognitive processing difficulties demonstrated by dyslexic readers. Furthermore, they can account for dyslexic characteristics outwith phonological skill and purely linguistic knowledge. Two main criticisms are levelled against sensorimotor deficit hypotheses, however. Specifically, some researchers question whether sensory deficits *cause* dyslexia, or whether they are co-morbid markers of the reading disability. A second criticism relates to *how* sensory deficits translate into a reading disorder.

Ramus and colleagues in particular propose a model of reading components in which a primary causal phonological deficit is often accompanied by co-morbid sensorimotor difficulties, but the sensorimotor deficits themselves have no bearing on the reading disorder. Ramus (2003, 2004) highlights the high incidence of co-morbidity between dyslexia and other developmental disorders, such as specific language impairment (SLI), autism, dyspraxia and Williams syndrome. Within this framework, ectopias affecting neurological correlates of phonological skill might also affect other regions, such as areas associated with visual perception or syntax. Thus, co-morbid visual symptoms have no more causal bearing on dyslexia than the syntactic deficit causing SLI. Figure 2 represents the causal hypotheses advocated by both phonological and magnocellular deficit hypotheses, in addition to how the magnocellular hypothesis purports to explain phonological and reading deficits. Figure 3 is a re-conceptualisation of the role of sensorimotor deficits in terms of co-morbid, non-causal characteristics in dyslexia.

Figure 2: Phonological and magnocellular theories of dyslexia, represented at biological, cognitive and behavioural levels of explanation (Based on Ramus, 2004; p. 721).

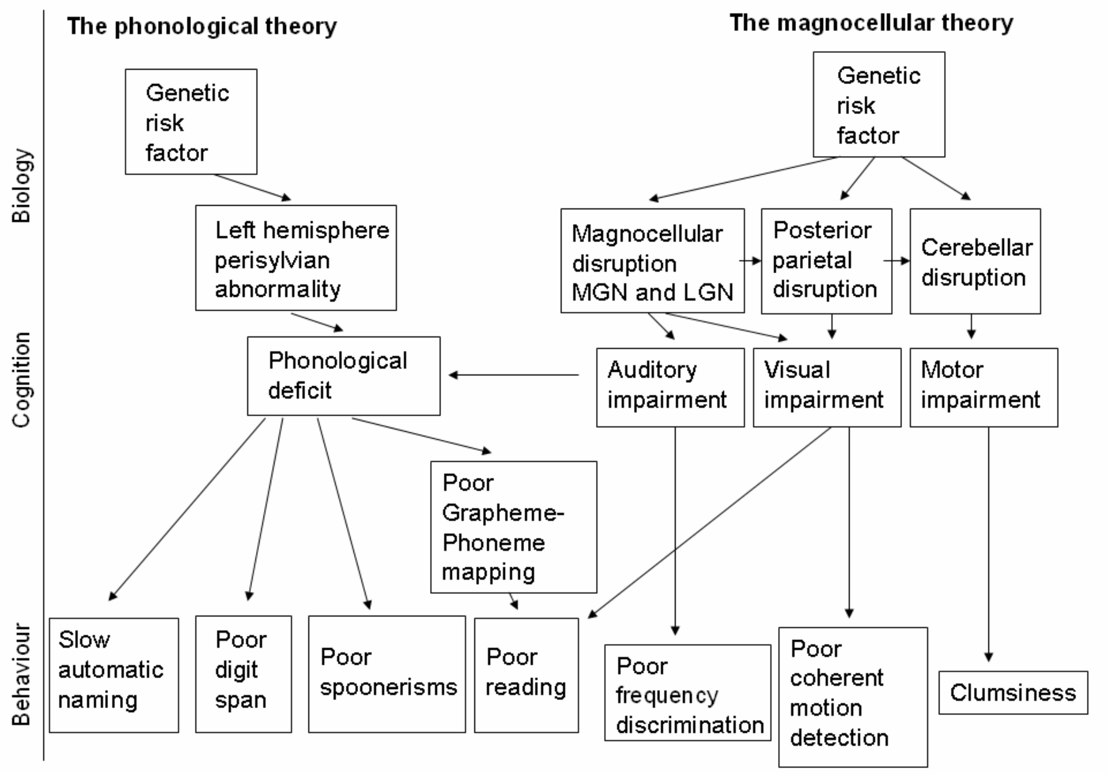
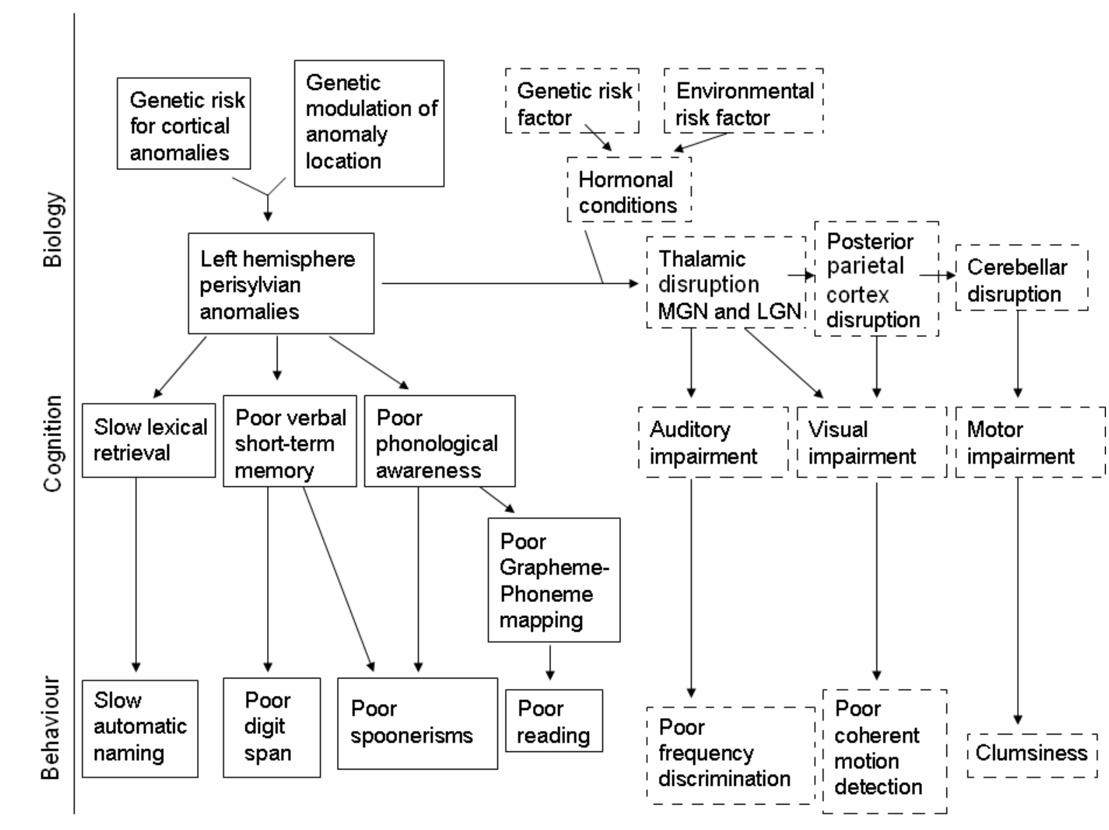


Figure 3: A re-conceptualisation of sensorimotor deficits and their role as co-morbid but non-causal characteristics of dyslexia (Based on Ramus, 2004; p. 721).



Note. Dotted lines represent genetic and cognitive markers of dyslexia, with no causal relationship to the reading disability.

Ramus argues that the occurrence of sensorimotor deficits and reading disability in dyslexia does not, therefore, imply a bottom-up causal connection between the two. Empirical evidence comes from studies suggesting that dyslexia can occur in the presence or absence of sensorimotor impairments (e.g., Ramus, 2003; White et al., 2006). Claims that an auditory processing deficit impedes the consolidation of adequate phonological representations (e.g., Tallal, 1980), for example, are criticised on the grounds that only a subset of dyslexics demonstrate auditory deficits (Amitay, Ben-Yehudah, Banai, & Ahissar, 2002; France et al., 2002; Heiervang, Stevenson, & Hugdahl, 2002). Similarly, only a sub-group of dyslexic readers demonstrate visual deficits (e.g., White et al., 2006), despite claims that visual impairments may cause putative phonological deficits (e.g., Cestnick & Coltheart, 1999). The phonological deficit, on the other hand, is pervasive.

Ramus and colleagues' conceptualisation of sensorimotor deficits as existent but irrelevant symptoms of dyslexia has been strongly opposed by Nicolson and Fawcett (2006). In response to White et al.'s (2006) study, Nicolson and Fawcett challenge methodological and conceptual points in the study. Despite evidence to suggest that naming speed is not merely an index of phonological retrieval, (Wolf & Bowers, 1999), White et al. classify the task as a phonological measure. Furthermore, White et al. found that over half of the dyslexic population suffered sensorimotor impairments, but conclude that because only phonological deficits are prevalent across the sample, the demonstrable sensorimotor deficits have no causal bearing on the reading impairment. This conclusion derives from the application of a unitary causal framework of dyslexia. Nicolson and Fawcett challenge this position citing alternative causal frameworks, in which dyslexia is viewed as a complex, multi-causal learning disability, of which there are several sub-types. In particular, they outline the need to divide components underlying reading ability in terms of phonology and fluency, rather than attempting to fit the data into a single phonological theory. In the following section, we will outline the theoretical and empirical justifications for considering phonological skill and fluency as separate components of reading ability.

2.4 The Double Deficit Hypothesis

The double deficit hypothesis of developmental dyslexia was formulated by Bowers and Wolf (1993) and refined by Wolf and Bowers (1999) and Wolf, Bowers and Biddle (2000). In a similar framework to Coltheart et al.'s (2001) dual route hypothesis, the theory derives from results (discussed in the following sections) indicating that phonological skill cannot explain all of the variance in reading measures (e.g., Cutting, Carlisle, & Denckla, 1998). Instead, there is evidence to suggest that the speed at which the reader can translate a visual symbol into a verbal label is independent of phonological ability and contributes unique variance to reading. The double-deficit hypothesis therefore postulates two independent causes of dyslexia: deficits in phonology and naming speed, which can occur independently or together in a 'double' deficit. We will now turn to descriptions of naming speed and its component processes as well as evaluating its proposed independence from phonological processes.

2.4.1 Rapid Automatised Naming

The neurologist Geschwind described the case of Dejerine, a patient with "pure alexia without agraphia": a visual-verbal disconnection, in which gross visual processing was intact, but lexical labels could not be produced (Geschwind & Fusillo, 1966). Dejerine's ability to match colours, but not produce their names demonstrated normal activation of spoken words to visual and kinaesthetic observations, but an inability to use that information for producing the appropriate lexical label. This finding presented an avenue for investigating cases of intelligent children who demonstrated a surprising inability to read well. Instead of finding an inability to name colours in such children, however, it was found that reading impaired or dyslexic children were slower and more hesitant, demonstrating a lack of 'automaticity' in naming (Denckla, 1972). Denckla and Rudel investigated this further, designing a serial naming task termed *Rapid Automatised Naming* (RAN). The original version of this task consisted of a visually presented array of 5 high frequency letters, digits, colours and common objects repeated 10 times in 5 rows. Although this is the format that is still widely used, RAN also incorporates tasks characterised by repeatedly naming familiar stimuli as quickly as possible. In the RAN, the participant's task is to name all of the stimuli from left to right across the page as quickly as possible, and over a number of experiments it was found that children with dyslexia were much slower than their peers in completing the RAN task. Furthermore, performance on the RAN was correlated with reading outcome measures (Denckla & Rudel, 1972; 1974; 1976a, b).

Since then, a substantial number of studies have corroborated the finding that RAN yields higher latencies in dyslexic as compared with average readers. These findings are true for children (Denckla and Rudel 1976a, b; Wolf 1982; Wolf 1986; Bowers 1988; Spring 1988; Wolff et al. 1990; Berninger 1995; Snyder and Downey 1995; Grigorenko, et al. 1997) as well as adults (Felton, Naylor, & Wood, 1990; Korhoren, 1995). Furthermore, dyslexic readers are slower at the task than non-discrepancy or *garden-variety* poor readers (Ackermann & Dykman, 1993; 1995; Badian 1994; Badian 1995; Badian 1996a; Badian 1996b; Wolf and Obregon 1992) and readers with other learning disabilities (Ackerman & Dykeman, 1993, 1995; Denckla & Rudel, 1976b; Felton, Naylor, & Wood, 1990), suggesting that slow rapid naming is a robust characteristic of dyslexia. Furthermore, RAN effects survive even when IQ (Badian, 1993; Cornwall, 1992; Hulslander et al., 2004) attention deficit disorder (Ackerman & Dykman, 1993; Compton, Olson, DeFried, & Pennington, 2002), socioeconomic status (Felton et al., 1990; Swanson, Trainin, Necoechea, & Hammill, 2003) and articulation rate (Parilla et al., 2004) are partialled out. Variations of the task involving *Rapid Alternating Stimuli* (RAS) such as letters and digits also reveal that very young dyslexic children are profoundly impaired (Wolf, 1986) relative to unimpaired readers.

2.4.2 Naming speed as an independent causal factor in reading ability?

The studies outlined above suggest that performance on RAN tasks can discriminate reading groups. However, RAN is often subsumed under the phonological task family, and a number of reading researchers consider RAN an index of "retrieval of codes from a long-term store" (Wagner, Torgesen, Laughon, Simmons, & Rashotte, 1993, p. 83). Despite this, there is ample research to suggest that RAN is an index of reading ability that is largely independent of phonological skill.

Firstly, a number of researchers have found only moderate interrelationships between RAN performance and phonological skill: In reading impaired samples, only modest correlations ($r = .35$; $r = .12$) are found between RAN and measures of phonological awareness (phoneme deletion and elision) (Cornwall, 1992; Goldberg, Wolf, Cirino, Morris, & Lovett, 1998). Similarly small correlations between RAN and a range of phonological tasks are found in samples of the general reading population (Blachman, 1984; Mann, 1984), and Felton and Brown (1990) found no significant correlations between RAN and phonological tasks (phonological awareness and phonetic recoding in memory). These findings in English are supported by cross-linguistic findings in German: in an unselected population of Grade 2-4 pupils, Wimmer (1993), for example, found little correlation between RAN and phonological awareness.

The bulk of studies investigating the relationship between RAN and phonology therefore yield only moderate relationships between these measures. One or two studies proved exceptions to this trend, finding significant correlations ($r = .40$; $r = .35$) in Grade 2 and 3 pupils (Bowers, Sunseth, & Newby-Clark, 1998; Wagner, Torgesen, Laughon, Simmons, & Rashotte, 1993). However, given that phonological retrieval is a requirement of RAN performance, the existence of a relationship between the two variables is to be expected. Of greater interest is the amount of variance that apparently cannot be accounted for by phonological ability (Wolf & Bowers, 1999).

A second line of research investigates the independent contribution of either RAN or phonological skill to reading outcome measures when the other variable has been partialled out. For example, a series of studies by Bowers and colleagues demonstrate that whilst phonological awareness predicts word and non-word identification, naming-speed measures are independently related to the accuracy and latency of word identification (Bowers, 1993, 1995; Bowers & Swanson, 1991). Furthermore, naming speed uniquely predicts expressiveness, reading efficiency and reading speed of text (Young & Bowers, 1995). RAN is therefore a consistent predictor of reading speed; otherwise known as fluency (deJong & van der Leij, 1999; Kirby, Parrilla, & Pfeiffer, 2003). Other studies also suggest that whilst phonological awareness is related to decoding ability, naming speed predicts later reading fluency (Manis, Doi, & Badha, 2000). Moreover, Parrilla, Kirby, and McQuarrie (2004) demonstrated that RAN remains an independent predictor of reading, even when prior reading ability has been partialled out. The independence of this relationship from the influence of phonological skill suggests that the component skills underlying fluency are qualitatively different from those underlying decoding ability (Wolf & Bowers, 1999).

Findings from English speaking populations are corroborated by cross-linguistic studies, demonstrating independent contributions to reading outcome measures from naming-speed and phonological awareness measures (e.g. Berninger et al., 1995; Blachman, 1984; Felton & Brown, 1990; Mann, 1984; Meyer, Wood, Hart, & Felton, 1998b; Naslund & Schneider, 1991; Van den Bos, 1998; Wimmer, 1993). Furthermore, evidence of naming-speed *deficits* are found in several European languages, such as German (Naslund & Schneider, 1991; Wimmer, 1993; Wimmer & Hummer, 1990; Wolf, Pfeil, Lotz, & Biddle, 1994), Dutch (Van den Bos, 1998; Yap & Van der Leij, 1993, 1994), Finnish (Korhoren, 1995), and Spanish (Novoa & Wolf, 1984). In relation to the predictive value of naming-speed, Wimmer (1993) and Wolf et al. (1994) demonstrated that naming-speed is a *better* predictor of reading ability in German than phonological skill. A feature of German that is common to many other European languages (e.g., Finnish, Spanish and Italian) is that the orthography is more transparent than in English: that is, there is a more predictable correspondence between the grapheme and its associated phoneme. As a result, children potentially at-risk of a reading impairment could learn to decode words relatively easily. Naming speed, however, as an independent component of reading does not vary as a function of orthographic transparency, and remains a difficulty for dyslexic children from a range of languages and scripts: Recent findings suggest the presence of naming-speed deficits in logographic languages such as Chinese, which do not require phonological decoding (Chan, Ho, Tsang, Lee, & Chung, 2003; Ho, Chan, Tsang, & Lee, 2002; Ho & Lai, 2000).

Whilst these studies provide a ‘snapshot’ of the independent influence of RAN on reading skill at a given developmental stage, the influence of phonological skill and RAN on reading measures at a later age have also been measured. Using an *autoregressive* variable (any given reading measure taken at two ages), it is possible to attain the predictive value of variables such as phonology and naming-speed on later reading measures when earlier performance on the reading measure itself is partialled out. Whilst this methodology is quite an effective means of controlling extraneous influences from the reading measure itself on future ability, results from these studies are often conflicting, reflecting the number of other variables that can potentially influence reading ability. Torgesen, Wagner, Rashotte, Burgess, and Hecht (1997), for example, found that phonemic awareness contributed to later word recognition, but a similar study by Meyer et al. (1998b) revealed naming speed as the only variable to predict later word identification.

In addition to including an autoregressive variable, studies predicting reading ability therefore need to account for a number of other potentially confounding variables, such as IQ, reading instruction, socio-economic status, and critically, the reading ability of the population studied. Controlling for these extraneous variables is particularly important when studying samples of high and low reading ability, since reading component measures may influence outcome measures (such as word identification) as a function of reading ability. In a comparison of reading predictors across groups of differing ability, for example, McBride-Chang and Manis (1996) found that whilst phonological awareness predicted word identification in both groups, naming speed was strongly associated with word identification only for the reading-impaired group.

Evidence of the independence of naming speed as an independent predictor of reading ability is therefore abundant, and endures even in tightly controlled regression analyses. These findings are the foundation for the double-deficit hypothesis put forward by Bowers and Wolf (1993) and the cognitive processing model outlined by Wolf and Bowers (1999) (see Figure 4, Chapter 3). A similar rationale forms the basis of a connectionist reading model by Manis, Seidenberg, and Doi (1999), in which RAN accounts for distinct variance in reading ability, owing to the arbitrary associations between print and sound (e.g. the digit and its name) in addition to other components that overlap with reading, such as speed and fluency. A prediction of the double-deficit hypothesis and the Manis et al. (1999) reading model is that if naming speed and phonological skill each contribute independently to reading ability, impaired function in either skill should also occur independently. Thus, sub-types of dyslexia should occur, reflecting either naming-speed or phonological deficits.

To investigate the occurrence of dyslexic sub-types Bowers (1995) and Wolf (1997) conducted two large-scale re-analyses of cross-sectional and longitudinal school samples in Canada and the United States. They divided the samples into four subgroups, using strict cut-off criteria on measures of phonological awareness and naming-speed. A convergent finding was that four subtypes of reading ability were consistently distinguished. One subset of children had no reading impairments at all; a second and third had either a naming-speed deficit or a phonological deficit; a fourth had double deficits in both naming-speed and phonology. The fourth group also represented the most profoundly impaired reading group in both samples. Replications of reading samples into similar sub-groups have been made by Lovett (1995) and Goldberg et al. (1998). Berninger et al. (1995) and Badian (1996a, 1997) also identified triple-deficit groups, the third impairment comprising orthographic problems. Reading sub-groups analogous to the double-deficit hypothesis were also obtained by Morris et al. (1998) using cluster analysis.

However, the validity of conclusions based on grouping children into different sub-types based on predictor variables that are correlated with one another has been questioned by Schatschneider, Carlson, Francis, Foorman, and Fletcher (2002). Their concern relates to the possibility that the more severe of the two deficits demonstrated by children with a double deficit could in fact be a statistical artefact. If two variables are correlated, a distortion is introduced to the cell means. For example, if RAN and phonological awareness (PA) are correlated (albeit moderately), the mean level of PA will be lower when both PA and RAN performances are low than when PA is low but RAN is average. The implication of this artefact on the double deficit hypothesis is that the group with a double deficit will have lower scores on PA than the group with PA deficits but no RAN deficits. The authors argue that any difference between the double deficit and single deficit PA groups may therefore be attributable to a more profound PA deficit in the former group, rather than a RAN deficit *per se*. The curvilinear relationship between PA and reading also increases the possibility of this confound: a profound phonological deficit has an *increasingly* profound effect on reading performance. Under this argument, RAN impacts on reading ability only as a function of the primary influence of phonological skill.

The statistical artefact identified by Schatschneider et al. highlights a need for caution in identifying dichotomous subgroups of reading ability, as advocated by the double-deficit hypothesis. However, it does not, as the authors argue, diminish the argument that naming speed can influence reading ability independently of phonological skill. As we have seen, regression analyses demonstrate that RAN performance contributes to reading outcome measures when phonological skill has been partialled out (e.g. Parrilla et al., 2004). Moreover, current on-line testing measures, such as neuroimaging, offer a means of validating the independence of naming-speed from phonological skill without recourse to correlating behavioural measures.

Anatomical regions associated with different reading component measures have been revealed by neuroimaging studies. Briefly, the *frontal reading system* (including the left inferior frontal gyrus) is implicated in phonological and semantic processing (e.g. Demonet et al., 1992; Zatorre, Evans, Meyer, & Gjedde, 1992). Regions specifically associated with phonological processing include the posterior and dorsal regions of the inferior frontal cortex (Poldrack et al., 1999). The *ventral posterior reading system* (comprising occipital and temporal lobes) includes the lateral extrastriate region, which correlates with orthographic processing (e.g. Price, Wise, & Frackowiak, 1996; Pugh et al., 1996). The *dorsal posterior reading system* (parieto-temporal regions), includes the angular gyrus, supramarginal gyrus, and posterior superior temporal gyrus. This system is largely involved in integrating orthographic and phonological information (Price, 2000; Pugh et al., 1996).

Using the map of the reading brain outlined above, Misra, Katzir, Wolf, and Poldrack (2004) conducted an fMRI study to investigate whether the processes underlying RAN-letters and -objects overlap with particular structures and their cognitive counterparts. The main findings indicated that although frontal regions associated with phonological processing were significantly activated, ventral and dorsal regions were also active, suggesting that RAN recruits visual processing, as well as binding visual and phonological information. These findings corroborate a proposal by Wolf and Kennedy (2003) that reading engages structures that originally evolved for other purposes, such as identifying and naming objects. Moreover, activation of frontal eye fields implicated the involvement of voluntary saccades, and basal ganglia activity reflected the task's demand for automaticity (Poldrack & Gabrieli, 2001). Although RAN-letters and –objects activated a number of similar areas, including areas associated with phonological processing, RAN-letters implicated a broader range of structures. Specifically, dorsal areas were significantly active, including the angular gyrus and superior parietal lobule associated with integrating orthographic and phonological information. The authors conclude that the neuranatomical structures activated during RAN-letters are similar to and reflect the complexity of processes activated during word reading. Whilst RAN certainly contains a significant phonological task element, therefore, the authors argue that its complexity distinguishes it from classification as a purely phonological task.

In summary, statistical artefacts can confound double deficit sub-groups (Schatschneider et al., 2002), but the bulk of evidence suggests that RAN is only moderately related to phonological skill, and RAN performance contributes independent variance to reading outcome measures related to fluency (Wolf & Bowers, 1999). Neuroimaging studies corroborate behavioural findings, suggesting that RAN taps into a broader range of reading systems than phonology alone (Misra et al., 2004).

2.5 Chapter Summary

In this chapter, we have described and evaluated the principal causal theories of developmental dyslexia, in addition to outlining which component processes influence reading ability. The double-deficit hypothesis outlines two causes of dyslexia: core phonological and naming-speed deficits, which can occur independently or comorbidly in the same individual. In the next chapter, we discuss what is known about the component processes underlying naming-speed performance.

CHAPTER 3

The elusive nature of Rapid Automatised Naming

3.0 Chapter Overview

In this chapter, we investigate the progress made to date in elucidating which component processes involved in RAN influence performance latencies. We then set out the methodology used in the thesis to investigate this further, and we explain how our approach will aid a better understanding of rapid naming and reading fluency.

3.1 What determines RAN performance?

As a behavioural task, Rapid Automatised Naming is deceptively simple, requiring the reader to name a series of familiar items. However, Wolf and Bowers (1999) underline the number of processes that need to be activated and the efficiency with which these processes should be integrated in order to complete the naming task at rapid rates.

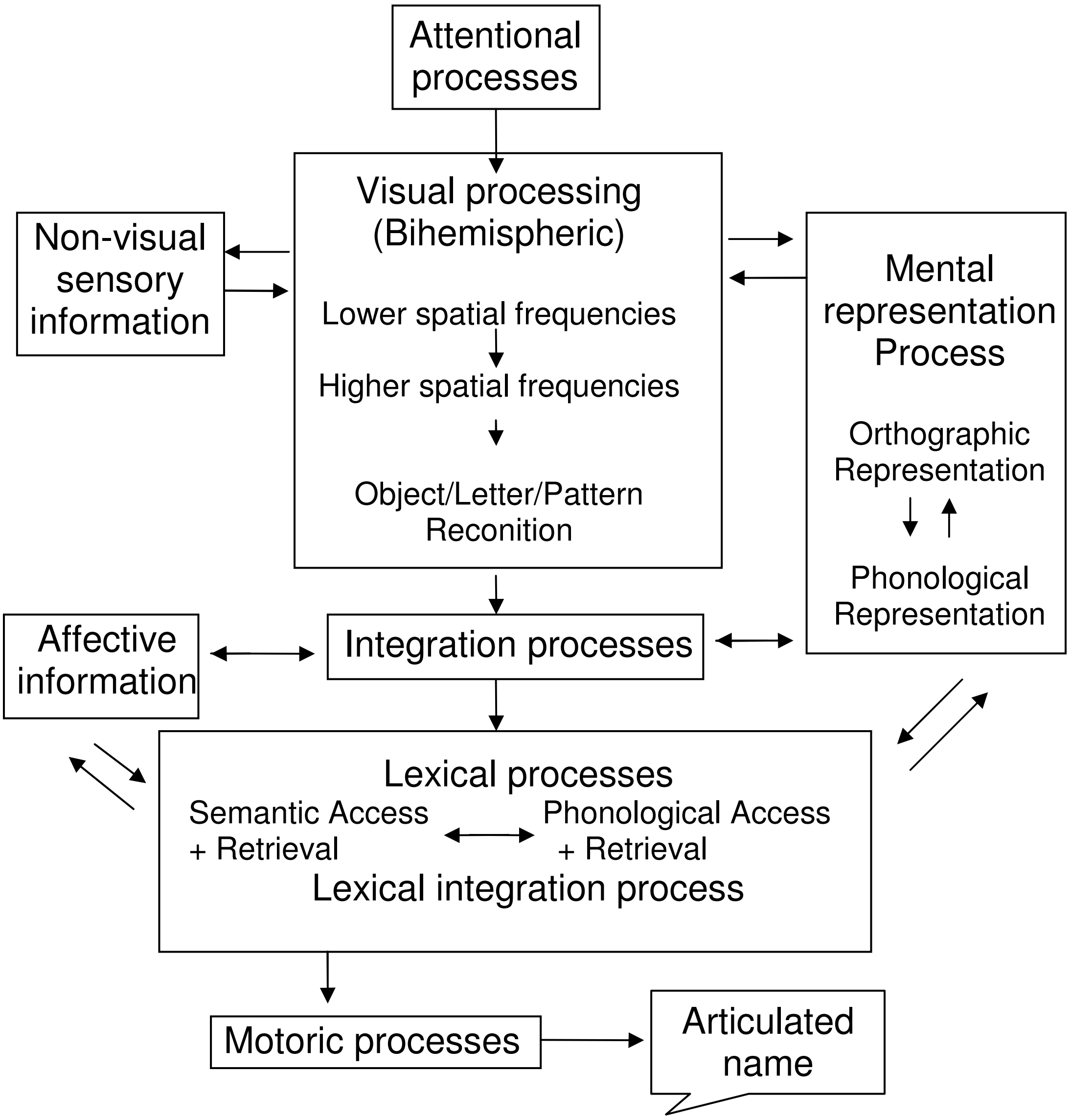
> …rapid automatized naming requires (a) attention to the letter stimulus; (b) bihemispheric, visual processes that are responsible for initial feature detection, visual discrimination, and letter and letter-pattern identification; (c) integration of visual feature and pattern information with stored orthographic representations; (d) integration of visual information with stored phonological labels; (f) activation and integration of semantic and conceptual information; and (g) motoric activation leading to articulation. Precise rapid timing is critical both for the efficiency of operations within individual subprocesses and for integrating across them(.) (1999, p. 418).

A current debate in reading research centres on which of these processes influence naming latencies, and in turn impact on reading fluency. A related question concerns which process(es), when aberrant, causes the naming-speed deficit characteristic of dyslexia.

Advocates of the phonological deficit hypothesis identify “retrieval of phonological codes from a long term store” (Wagner, Torgesen, Laughon, Simmons, & Rashotte, 1993, p. 84; see also Shankweiler & Crain, 1986; Share, 1995; Torgesen et al., 1997; Torgesen & Burgess, 1998) as the primary influence on naming speed and cause of the naming-speed deficit. Clarke, Hulme, and Snowling (2005), for example, hypothesise that a deficit in retrieving phonological codes limits the resources available to effectively perform executive processes such as inhibition: a primary phonological deficit therefore yields a secondary attention deficit in relinquishing stimuli that have already been named and starting to process subsequent stimuli.

An alternative position, based on findings such as those outlined in the previous section, is that RAN speed is potentially determined by *all* of the processes activated as well as the efficiency with which they are integrated. A RAN deficit can therefore occur as a result of impaired activation at any processing stage and/or as a result of difficulty in integrating different processes (see Figure 4).

Figure 4: Model of visual naming for letter(s) stimulus. (Taken from Wolf & Bowers, 1999; p. 417).



Despite a large corpus of studies measuring the independence of RAN as a behavioural task and its contribution to reading outcome measures, surprisingly few researchers have attempted to unpick the processes underlying rapid naming (Georgiou, Parrila, & Kirby, 2006). As a result, we do not currently have a complete understanding of how RAN influences reading (i.e. which components are critical in determining naming performance) (Kirby et al., 2003). Neuhaus, et al. (2001) argue that measuring RAN components is essential to our understanding of what RAN measures, and how it is related to reading. In the following section, we outline attempts to elucidate the component processes of RAN that influence reading measures and RAN performance itself.

3.2 Which components of naming speed influence reading measures and RAN performance?

A number of early experiments demonstrated that continuous (serial list) presentation of items in RAN contributes more variance to reading measures than discrete lists (Bowers & Swanson, 1991; Fawcett & Nicolson, 1994; this finding is pursued in more detail in Chapter 4). Similar methods of decomposing RAN processes have also been employed to determine whether articulation times (measured by the duration of the speech sound response to the stimulus) or pause times (measured by the duration of the silence between speech sounds) have the greatest bearing on reading ability. Whereas articulation times reflect the verbal-motoric response to the item, pause times include disengagement from the named item, and sensory and cognitive processing of the next stimulus to be named (Wolf & Bowers, 1999).

Studies investigating which component predicts reading ability have produced conflicting results. Anderson, Podwall and Jaffe (1984) conducted the first study to compare articulation and pause times in a study comparing dyslexic and average 8-10 year olds. Their findings indicated that articulation times and pause times were longer for dyslexic readers. However, Obregon (1994) later demonstrated that an adolescent dyslexic group demonstrated longer pause times when compared with an average reading group, but group performances did not differ on errors, articulation times or end-of-line scanning time. Similarly, Neuhaus et al. (2001) found that only RAN-letters pause times predicts reading, which prompted the authors to identify letter-naming pause time as an “index of verbal attention that affects performance on a variety of lexically based tasks” (p. 370). These findings were replicated in an older sample (Neuhaus, Carlson, Jeng, Post, & Swank, 2001), and a longitudinal study by Cobbold, Passenger and Terrell (2003) showed that variability in RAN tasks in addition to word-reading were attributable to pause times, but not articulation times. Recently, Georgiou et al. (2006) also demonstrated that RAN pause times strongly predicted reading accuracy and fluency at the end of Grade 1 (6-7 years), whereas articulation times demonstrated weaker correlations with reading measures.

Results indicating a predictive role for articulation have also been found in naming studies (Fawcett & Nicolson, 2002; Neuhaus & Swank, 2003) as well as in more general type studies. However, the relationship between articulation and reading ability tends to be weak and inconsistent, which contrasts with the consistency with which pause times predict RAN performance and reading ability. Understanding the processes underlying pause times may therefore address many unanswered questions regarding factors influencing RAN performance and reading ability.

Wolf and Bowers (1999) suggest that pause times reflect the disengagement of attention from a named item in order to begin processing the next item in the list, whilst Neuhaus et al. (2001) identify a schism between pause times in RAN-Letters, reflecting a specific processing speed associated with letters, and RAN-Objects, reflecting general verbal processing speed, or lexical access. These accounts are potentially useful to begin segmenting the behavioural requirements of rapid naming. However, behavioural measures are restricted to descriptive levels of explanation, and they do not directly elucidate the specific processes involved in naming, such as attention in addition to visual and phonological processing. It is only by clearly specifying the processes involved in the task and empirically testing these processes (and ideally, their neural correlates) that a picture emerges of the factors involved in causing RAN ability and the RAN deficit characteristic of dyslexia.

Firstly, a distinction should be made when discussing pause time, concerning processing of surrounding letters and processing of the current letter itself (i.e. the next to be named). The processes underpinning the current letter are outlined in Wolf and Bowers' (1999) naming model (p. 417; Figure 4 in this thesis) beginning with attention to the stimulus, followed by visual feature detection and orthographic matching, culminating in phonological (and semantic) retrieval and articulation. However, serial RAN involves effective inhibition of previous (already named) stimuli (Wolf & Bowers, 1999) and pause times can arguably also reflect preliminary processing of the next item to be named (provided by information from the parafovea; the area surrounding fixated areas). Both inhibition and parafoveal processing impairments have been identified in dyslexic readers (e.g., Hari & Renvall, 2001; Lorusso et al. 2004), and we will return to details of these impairments in chapters 6 and 7).

Wolf and Bowers (1999) outline potential causal factors in RAN performance, and their argument is framed in two non-exclusive hypotheses of the naming-speed deficits in dyslexic readers. Both causal hypotheses are traceable to earlier processing stages than phonological retrieval and this model presents a means of testing whether processes other than phonology influence RAN performance and contribute to the dyslexic naming-speed deficit.

One hypothesis outlined by Wolf and Bowers (1999) relates naming-speed impairments to a domain-general *speed-of-processing* deficit, which is prevalent across perceptual, motoric and linguistic domains (Breitmeyer, 1993; Chase, 1996; Farmer & Klein, 1995; Lovegrove & Williams, 1993; Tallal, Miller, & Fitch, 1993; Willows, Kruk, & Corcos, 1993; Wolf et al., 2000). Perceptual findings, for example, suggest that dyslexic readers do not process low-level information as quickly as average readers (Breznitz & Misra, 2003; Buchholz & Davies, 2005; Chase & Jenner, 1993; Facoetti, Lorusso, Cattaneo, Galli, & Molteni, 2005; Farmer & Klein, 1995; Greatrex & Drasdo, 1995; Lehmkuhle, 1993; Lovegrove, 1993; Meyler & Breznitz, 2005). Visual tasks such as persistence, temporal-order judgement, flicker sensitivity and metacontrast demonstrate impaired accuracy and latency relative to average readers (e.g., Breitmeyer, 1993; Demb, Boyton, Best, & Heeger, 1998; Eden, et al., 1995; Galaburda, & Livingstone, 1993; Hayduck, Bruck, & Cavanagh, 1993; Meyler & Breznitz, 2005; Slaghuis, Lovegrove, & Davidson, 1993; Willows, et al., 1993; Wright & Groner, 1993; Zeffiro & Eden, 2000).

Similar findings are found in the auditory modality in temporal order tasks (Overy, Nicolson, Fawcett, & Clarke, 2003; Helenius, Uutela, & Hari, 1999; Stein & McAnally, 1995; Tallal, 1980; Tallal et al., 1993; Tallal, Merzenich, Miller, & Jenkins, 1993; Witton et al., 1998). Whilst these findings are not always replicated (visual tasks: Greatrex & Drasdo, 1995; Johannes, Kussmaul, Munte, & Magnun, 1996; auditory: Share, Jorm, Maclean, & Matthews, 2002), the majority of the evidence suggests the involvement of multi-modal perceptual processing speed deficits in dyslexia.

Complex motoric tasks also discriminate dyslexic and average reading groups. Finger-tapping tasks, for example, involving tapping to asynchronous rhythms, yield lower rates of accuracy for dyslexic readers (Wolff, 1993; Wolff, Michel, & Ovrut, 1990 a, b; Fawcett, Nicolson, & Dean 1996; Nicolson & Fawcett, 1994). Nicolson, Fawcett and colleagues have also identified difficulties in balance, motor control, and muscle tone; which they attribute to cerebellar affision (Nicolson et al., 2001). Motoric symptoms become increasingly impaired when dyslexic children and adults are required to perform a motoric task *and* a second task. Balancing on beams, for example, is more difficult for dyslexics than average readers when they are given an additional task, such as counting (Fawcett & Nicolson, 1992; Needle, Fawcett, & Nicolson, 2006; Nicolson & Fawcett, 1990).

Slow speed of processing is therefore a prominent characteristic of dyslexia, and its generality across modalities has led a search for its cause at a basic, neuronal level. Llinas (1993) proposed that specific neurons might be directly responsible for the regulation of timing, and the inferior olive in the cerebellum and the intralaminar nucleus in the thalamus are hypothesised sub-cortical loci. Such a deficit would be a potential neurological locus of the processing speed deficit observed behaviourally across modalities, and could be the means of reconciling more abstract causal hypotheses of dyslexia, such as the processing speed deficit hypothesised by Wolf and Bowers (1999) with its subcortical analogue, such as a cerebellar deficit (e.g., Nicolson & Fawcett, 2006).

However, findings indicate that when performing simple tasks, involving a single stimulus such as pure tones, dyslexic readers perform as accurately as average readers (e.g. Nicolson & Fawcett, 1993 a, b; Watson, 1992; Watson & Miller, 1993). Dyslexic readers can correctly perceive interaural phase modulations and temporal cues of less than 1ms (Hari, Saakilahti, Helenius, & Uutela, 1999; Witton et al., 1998), suggesting normal phase locking of sound perception. In general, tasks that discriminate dyslexic from non-dyslexic readers are complex, and require rapid and simultaneous processing of multiple items (Farmer & Klein, 1993; Godfrey, Syrdal-Lasky, Millay, & Knox, 1981; Tallal, 1980; Tallal et al., 1993; Werker & Tees, 1987).

Thus, Hari and Renvall (2001) propose that rather than a direct link between processing speed and inter-neuronal abnormalities *per se*, difficulties in rapid stimulus processing are due to impaired triggering of automatic attention or Sluggish Attentional Shifting (SAS), which mediates neuronal impairments and behavioural characteristics of dyslexia. Within this framework, the authors propose a cascade of causal factors; starting with magnocellular function, filtering down to parietal-lobe-supported attentional capture, which has repercussions for multi-modal attention shifting and processing speed.

The proposed magnocellular neuronal route is not the only possible causal hypothesis for an attention deficit however. Attention deficits or failure to automatise routine behaviours and processing of familiar stimuli have been identified as possible mediator between processing speed deficits, demonstrated behaviourally in the RAN and cerebellar abnormalities (e.g., Fawcett & Nicolson, 2001, p. 100). Specifically, sub-vocalisation skills associated with cerebellar activity (Thach, 1996) are proposed to influence reading fluency rates. A cerebellar *impairment* might therefore impede sub-vocalisation, with repercussions for the automaticity with which lexicalised stimuli are retrieved and how fluently text can be read.

Currently, the precise neural locus or loci of the processing-speed deficit remains a subject for debate. Irrespective of its etiology, however, there is strong evidence to suggest that a processing speed deficit impairs rapid naming latencies as well as other measures of reading fluency. Using ERPs, Breznitz and colleagues have been instrumental in demonstrating slower temporal activation of perceptual and cognitive processes in dyslexics relative to average readers. Breznitz (2005) found that effective RAN performance was related to a P200 peak latency (associated with feature detectection, e.g., Luck & Hillyard (1994), and other early sensory stages of item encoding; Dunn, Dunn, Languis, & Andrews, 1998), whilst an age matched group of young dyslexic adults peaked at P300 (associated with dynamic updating of information in working memory; e.g., Fitzgerald & Picton (1983) and cognitive allocation and task involvement; Kramer, Strayer, & Buckley, 1990). This finding suggests that average and dyslexic readers' RAN performance is mediated by different RAN processing requirements: whilst average readers benefit from processing perceptual detail, dyslexic readers are faster at RAN when they succeed in allocating attention and memory processes effectively. Similar processing speed differences have been demonstrated in the visual and auditory modalities across low-level non-linguistic (tones and shapes) and linguistic tasks (phonemes and graphemes) in addition to higher level orthographic and phonological processing. Dyslexic readers generally process stimuli more slowly, but crucially, children with dyslexia demonstrate a consistently longer delay between visual / orthographic and auditory / phonological processing (Breznitz, 2003). Speed of processing gaps are also found in compensated (university level) dyslexic students, but only at higher processing levels (orthographic and phonological stages) (Breznitz & Misra, 2005; Breznitz & Meyler, 2005). The authors propose that the speed of processing deficit characteristic of dyslexia reflects *asynchronous* processing of visual and auditory information, whereby temporal binding of the two components is more difficult for dyslexics (also see Breznitz, 2006). The finding is persistent in adults, but low-level information may at least have been automatized by this stage of development.

Empirical work therefore supports the domain-general processing-speed deficit outlined by Wolf and Bowers (1999). Evidence that processing speed deficits are multi-modal and increase as a function of task complexity are proposed to reflect a generic attention deficit, rather than an inter-neuronal timing deficit (Hari & Renvall, 2001), which mediates speed of processing and potential neuronal and sub-cortical anomalies proposed to contribute to dyslexic characteristics (e.g., magnocells and the cerebellum). Irrespective of the processing speed deficit's cause, however, evidence from ERP studies suggest that it influences rapid naming performance as well as other low and high level processes related to reading ability.

In addition to the domain-general hypothesis, Wolf and Bowers (1999) outline another - modality-specific - route by which processing stages prior to phonological activation might result in the naming speed deficit. Slow visual processing speed is a hypothesised cause of higher RAN latencies (Bowers & Wolf, 1993; Wolf & Bowers, 1999) and it is argued that a deficit at the visual level would impact on naming speed and reading by a) impairing connections between orthographic and phonological units, b) preventing the development of clear orthographic representations, and c) increasing the amount of practice required in order to obtain adequate orthographic representations. A delay at the visual stage would therefore make it difficult to recognise and produce names for familiar stimuli at automatised rates, which would cause longer pause times between items in the RAN, and ultimately, reading speed would become less fluent (Wolf & Bowers, 1999).

Research into potential visual deficits in dyslexia is prolific, but causal theories of specific deficits are constantly evolving, owing to inconsistency in the results. Studies show evidence that visual impairments unrelated to magnocellular deficits are found in dyslexic readers (Amitay, Ben-Yehudah, Banai, & Ahissar, 2002; Farrag, Khedr, & Abel-Naser, 2002; Skottun, 2000). Furthermore, attempts to relocate magnocellular deficits as impacting on dorsal stream processes, affecting the *attention spotlight* involved in reading (e.g., Vidyasagar, 2004), have been criticised by Skottun and Skoyles (2006), owing to misclassification of tests thought to index magnocellular function. Findings potentially relevant to RAN processes, such as impaired visual attentional sequencing (e.g. Whitney & Cornelissen, 2005), have also recently been contradicted in a study by Hawelka, Huber, and Wimmer (2006): analogous beginning and end position advantages of letter strings were found between dyslexic and average readers. Whilst progress has been made in identifying potential visual impairments in dyslexia therefore, we are far from a comprehensive theory of how visual impairments impact on all aspects of reading behaviour, including naming speed deficits.

3.3 Thesis aims and methodological considerations

From the review above, it is clear that some progress has been made in terms of uncovering the influential components of naming speed and reading fluency. Few of these results elucidate whether naming and fluency represent core phonological skills, however, or whether Wolf & Bowers (1999) are correct in their hypothesis that attentional and visual processes are also critical to reading fluency. The aim of this thesis is to examine whether extra-phonological processes (attentional and visual) influence reading fluency. As we have seen, the Rapid Automatised Naming task is a consistent predictor of reading fluency (e.g., deJong & van der Leij, 1999; Kirby, Parrilla, & Pfeiffer, 2003). We therefore use manipulations of this task to elucidate which low-level component processes influence naming speed and hence reading fluency. The research outlined in this thesis follows the tradition in reading research of using RAN as an index of reading fluency (see Wolf & Bowers, 1999), but we include a number of modifications to the methodological approach usually employed.

To date, no studies have attempted to compare average and dyslexic reading groups on variations of the RAN designed to tax different component processes of naming-speed tasks. This thesis represents the first attempt to elucidate the component processes involved in RAN, using experimental comparisons of RAN versions across adult samples of dyslexic and average reading groups. Wolf and Bowers' (1999) cognitive naming model predicts that if extra-phonological processes influence naming speed and contribute to the naming-speed deficit, then processes occurring before phonological activation (such as attentional and visual processes) should exert an influence on naming-speeds, and should differentiate naming-speed performances for reading groups of dyslexic and average readers. Secondary aims of this thesis are to examine which component reading measures (e.g., word / non-word reading) vary as a function of RAN performance, and to investigate the root of a potential visual deficit. In the following sections, we set out the rationale for certain methodological decisions concerning the experiments presented in this thesis.

3.3.1 Using the RAN to investigate reading fluency

In this thesis, the RAN will be used in order to investigate reading fluency. As discussed in this chapter, RAN performance is highly correlated with and contributes independent variance to reading fluency (Bowers, 1993, 1995; Bowers & Swanson, 1991; deJong & van der Leij, 1999; Kirby, Parrilla, & Pfeiffer, 2003 Young & Bowers, 1995). Wolf and Bowers (1999) propose that the nature of this relationship stems from overlap in RAN processes and the low-level processing requirements of reading fluency. At this point in the thesis, it is necessary to define what we mean by the term ‘low level’. When the individual reads text, she is required to accomplish perceptual and phonological processing of the text, and in fluent readers, this process becomes *automatised* (Wolf & Bowers, 1999). Automatised processing of familiar items as represented by RAN tasks are defined by the minimal conscious effort employed when retrieving and articulating lexicalised names. Further, repeated presentation of items within RAN means that their visual and phonological representations are active shortly after the task has begun. Thus, RAN is not necessarily a measure of the rapidity of retrieval from a long term store. Rather, it is an index of the rapidity with which an item can be translated from its highly familiar visual form into a phonological form, which can then be articulated.

In normal reading, however, the individual is also required to process higher order semantic and syntactic information. The influence of these later processes on reading fluency is not the focus of this thesis, however. Rather, our concern is to explain how the attentional, perceptual and phonological processes involved in automatised retrieval of lexicalised, familiar items influence reading fluency. One potential criticism of this approach is that in removing the complex number of processes involved in reading text, it is difficult to generalise from the RAN to reading fluency *per se*. We argue, however, that in order to experimentally manipulate attentional, perceptual and phonological processes, it is necessary to remove other factors in the first instance. Our stance in this respect reflects the novelty of the current approach and is perhaps analogous to lexical and naming studies in psycholinguistics, which have since evolved to encompass more ecologically valid explanations of language processing in more naturalistic contexts (Clark, 1992).

Having decided upon the RAN as a measure of attentional, perceptual and phonological factors in reading fluency, we then decided more specifically to use the RAN-Letters throughout this thesis, for two reasons: First, letters represent the smallest representations of orthographic units, or 'graphemes'. As such, we maintain a less arbitrary connection between fluency and the low level processes involved in fluency represented by the RAN. A second, and related point, is that alphanumeric versions of RAN (letters and digits) are more consistent predictors of reading across development (compared with object and colour naming, which involve a greater semantic component). Kirby, Parrila, and Pfeiffer (2003) demonstrated that RAN-Letters becomes an increasingly strong predictor of reading ability with increased grade level. Further, alphanumeric versions of RAN are unique in their continued relationship to reading ability: RAN-Objects and RAN–Colours tend to have a weaker relationship with reading from Grade 2 onwards compared with alphanumeric RAN (Badian, 1996; Semrud-Clikeman, Guy, & Griffin, 2000; Wolf et al., 1986). The RAN-Letters continues to predict reading ability into adulthood (Shaywitz et al., 2000).

3.3.2 Group difference versus regression analyses

Results from the regression analyses reviewed in Chapters 2 and 3 demonstrate that performance on the RAN can only partly be explained by variation in phonological ability (e.g., Cutting, Carlisle, & Denckla, 1998). These findings suggest that phonological RAN components cannot explain all of the variance in RAN. As suggested by the review above, extra-phonological factors have been broadly implicated in dyslexia (e.g., Cornelissen et al., 1998; Nicolson & Fawcett, 1990; Hari

& Renval, 2001), but thus far, regression analyses investigating the role of extra-phonological processes on RAN, such as visual factors, are few in number (e.g., Jones et al., in press). Even when these studies are considered, regression analysis can only *associate* components of naming with naming speeds. In isolation, these studies can provide no indication of the *direct* influence of these components on RAN naming times, however.

In her proposed 'neuroconstuctionist' approach to developmental disorders, Karmiloff-Smith (1998) suggests that a key factor in understanding disorders such as dyslexia is to separate behavioural outcomes from underlying cognitive processes. Although RAN is a simplified measure of fluency (as it does not involve semantic and syntactic processes), it nevertheless represents a behavioural measure, comprised of a number of cognitive processes. In order to test which of these processes influence fluency, this thesis presents a number of experimental manipulations of RAN, designed to tax different processes involved in the original version of the task (Denckla & Rudel, 1976). In so doing, we can investigate a) which component processes influence RAN performance for skilled readers and b) which processes, when impaired, affect RAN performance, and fluency, for dyslexic readers. We supplement these findings with results from regression analysis to investigate how RAN relates to higher, word reading performance (Chapter 5) in addition to lower, visual processing ability (Chapter 8).

3.3.3 Adults versus children

Studies investigating the etiology of dyslexia often focus on child samples. Indeed, Karmiloff-Smith (1998) argues that studying the end state of development in older children and adults ignores the dynamics of development. Rather than charting the *development* of reading fluency, however, this thesis aims to identify which cognitive processes influence fluency. We argue that as a starting point, adult samples may be more appropriate for investigating this issue. First, as Szenkovitz and Ramus (2005) point out, psycholinguistic tasks are difficult for children, and in tasks measuring RT, performance is highly susceptible to extraneous influences. This view is also held by

Wolf and Bowers (1999, p. 420). As we shall see, for example, in Chapter 5, RAN measures in adult samples are also subject to error variance, but they are likely to be minimal compared with what we might expect from children. A second reason for conducting experiments with adults for the purposes of this thesis is to minimise the risk of comorbid learning disabilities. For example, dyslexia frequently co-occurs with Attention Deficit Hyperactivity Disorder (ADHD) (Nicolson & Fawcett, 1990; Shaywitz, Fletcher, & Shaywitz, 1995; Willcutt, Pennington & DeFries, 2000), and 15-25% of children diagnosed with a reading disability also meet criteria for ADHD (Willcutt et al., 2001; Willcutt & Pennington, 2000). University students, on the other hand, are high-functioning by necessity. They are therefore unlikely to represent members of the dyslexic population with comorbid disabilities. A caveat here is that we cannot rule out comorbidity within samples from a University population, and a further preventative measure is to ask participants about their developmental history (in terms of other known disabilities). In sum, we expect this thesis to reveal the component processes influencing reading fluency when the individual has maximum resources at their disposal. Despite their reading impairment, the dyslexic groups' compensatory strategies provide them with an opportunity to overcome difficulties associated with reading (Fink, 1998). Our method therefore represents a conservative measure of the components underlying fluency, since future projects may find stronger or more pervasive effects in younger or lower functioning populations.

3.3.4 Latency versus accuracy

RAN is primarily a measure of processing speed for lexicalised items (Wolf & Bowers, 1999). As such, this thesis conforms to previous studies and defines RAN performance as an RT measure. As noted by Denckla and Rudel (1972), dyslexia does not comprise an *inability* to name items. Rather, the naming process is more laborious than is the case with skilled readers, which is manifest in slower latencies rather than errors.

Group differences in the number of errors are often, but not always reported in RAN, primarily because they are difficulty to interpret. The naming-speed literature is relatively silent with regards to whether errors should be reported and how they should be interpreted, but we can make some conclusions here based on relevant discussions in the word production literature. Meyer (1992), for example, underlines the limited role of error data in representing only instances in which the production system breaks down. The author posits that a more fruitful avenue of research is to measure latency as indicative of the normally functioning production system. However, it can also be argued that errors provide information concerning the limits of our word production system. With reference to dyslexia, it might be hypothesised that access to underspecified orthographic and phonological representations required for RAN may lead to higher error rates as well as latencies. The evidence for this hypothesis in the RAN literature is mixed. Wolf (1986) demonstrated no difference between error rates for dyslexic and control children on versions of RAN, but other studies have suggested higher error rates for dyslexic children compared with controls (Stanovich, 1981; Vellutino et al., 1996). In this thesis, experiment 2 onwards will measure group differences in the proportion of errors, and experiment 5 will investigate the types of errors made (phonological versus visual). Because of the uncertainty concerning the reliability of error rates in elucidating RAN processes, however, we report these results for the sake of thoroughness and interpret the findings with reference to results from the RT measures.

3.3.5 Establishing a reading difficulty in 'dyslexic' groups

One of the difficulties with dyslexia research is that because the cause of dyslexia remains a matter of debate, there is no one established definition of the reading difficulty. Further, the definitions tend to be vague, prone to circularity, and confused in terms of providing a causal explanation of dyslexia versus functional diagnostic criteria. A common definition of dyslexia is represented by the World Federation of Neurology:

> [Dyslexia is] a disorder manifested by difficulty in learning to read despite conventional instruction, adequate intelligence and sociocultural opportunity.

> It is dependent upon fundamental cognitive disabilities which are frequently of constitutional origin (Critchley, 1970).

In addition to being vague and perhaps over-inclusionary, such definitions are based on exclusion rather than providing a definition of dyslexia. In response, some researchers have proposed positive definitions of dyslexia. Stanovich (1981), for example, proposed that dyslexia should be assessed when the individual has phonological deficits, on the reasoning that phonological deficits in dyslexia tend to be prevalent. Whereas the previous definition suffers from being too vague, however, Stanovich's approach runs the risk of being insufficiently comprehensive to include all forms of dyslexia. Moreover, studies seeking to investigate the *cause* of dyslexia who abide by Stanovich's criteria are more likely to find deficits of a phonological nature than is perhaps representative of all persons with dyslexia in the population.

A popular method of assessing dyslexia is the *discrepancy based* approach (e.g., Rutter & Yule, 1975), whereby a dyslexic profile incorporates average to high IQ levels, but low scores on literacy measures. Whilst fruitful in distinguishing persons with dyslexia from *garden variety* readers, this approach is also fallible. Vellutino et al. (1996), for example, demonstrated that figures based on the discrepancy based approach are typically over-inclusionary, including children who have received inadequate tuition. Further, Verbal IQ is correlated with reading ability, and may be a consequence of difficulty with reading (Stanovich, 1986). As such, definitions based on this criterion are prone to excluding individuals with dyslexia on account of their demonstrably low IQ. Snowling (2000) points out that these measures are unreliable in distinguishing dyslexia unless independent measures of literacy (e.g., spelling, reading) are also included.

Differences in Verbal IQ between 'dyslexic' and 'non-dyslexic' groups can therefore make a study vulnerable to a Type I or II error concerning an individual's dyslexic status. Goswami (2003) suggests that experimental studies investigating the causes of dyslexia should therefore employ a number of criteria to ensure valid differences in reading ability between groups. With reference to adult populations, similar Verbal and Performance IQ scores are required across groups. Further, members of the ‘dyslexic’ group should have been independently verified (formally assessed) as dyslexic prior to testing.

In this thesis, our aim is to compare the performance of dyslexic and non-dyslexic groups on variations of the RAN task. As such, we selected age-matched dyslexic and non-dyslexic groups according to the following criteria: Members of the dyslexic group were required to have been formally assessed by an educational psychologist before the age of 16. We also accepted a small number of participants that had been formally assessed during their undergraduate training by a staffmember of the university disability office. Background tests were used in order to establish valid group differences and were also used as inclusion criteria for individual participants.

We required there to be no significant differences between reading groups on IQ tests. Performance (non-verbal) IQ measures (Raven’s Advanced Progressive Matrices; Raven, Raven & Court, 1998) were administered from Experiment 2 onwards (substituted by the *Block design* task, WAIS; Wechsler, 1992 in Experiment 5). A Verbal IQ measure (the *Vocabulary* section from WAIS; Wechsler, 1992) was not included until Experiment 5, but as we shall see, despite a group difference on this measure, it did not explain the variance attributed to manipulations of the RAN task.

Tasks measuring literacy in this thesis comprised spelling and word recognition tests (Wide Range Achievement Test [WRAT-3]; Wilkinson, 1993) in addition to a non-word reading test (Patient Assessment Training System (PATSy) battery; Lum, Cox, Kilgour, Snowling, & Haywood, 2005) and exception word reading (Manis, Seidenberg, Doi, Chang, & Petersen, 1996), measuring phonemic decoding and whole word recognition respectively (see Appendix A and B). A Spoonerisms task (Hatcher, Snowling, & Griffiths, 2002) was also included as a measure of Phonological Awareness in Experiment 5. Forwards and backwards digit span measures were also used (Bangor Dyslexia test; Miles, 1993) to measure short term and working memory capacity for verbal information. The use of these measures in the thesis allowed us to gauge the validity of our ‘dyslexic’ and ‘non-dyslexic’ groups.

Despite the emphasis on naming speed processes in this thesis, we did not make claims as to the distribution of *single* versus *double* deficit individuals within the dyslexic group. The reason for this is that our samples typically comprise 20 individuals per group in each experiment and were therefore too small to generalise across the population. We did, however, use the double deficit distinction in order to determine whether assigning individuals to the dyslexic group is valid. Snowling (2000) advocates the Orton Dyslexia Society (1994) definition of dyslexia, which emphasised the importance of word-decoding difficulties in making an assessment. In our view, fluency should also be taken into account in this definition. As such, we excluded data from individuals assigned to the dyslexic group who demonstrate no indication of poor performance in either phonological skill or RAN (or both). Thus, individuals in the dyslexic group obtaining RAN scores 1.5 standard deviations above the non-dyslexic mean on RAN measures, who also showed no evidence of a phonological difficulty, were excluded from the analysis.

3.4 Chapter Summary

In this chapter, we have summarised the current progress towards understanding the component processes underlying naming speed and what causes the naming-speed deficit in dyslexia. In order to fully understand the processes underlying RAN, and therefore the low-level processes underpinning reading fluency, we argue that direct experimental manipulation of the task is necessary. In the following chapters, we present six experiments in which dyslexic and non-dyslexic groups are compared on manipulated versions of the RAN.

CHAPTER 4

What is special about naming continuous lists?

4.0 Chapter Overview

In the previous chapter, we outlined the rationale for using the Rapid Automatised Naming task as a means of investigating the low-level processes underlying reading fluency. We therefore begin our investigation by examining the behavioural requirements of the RAN task. Experiment 1 is a controlled manipulation of the main processing requirements involved in *continuous* versions of the task that influence dyslexic and non-dyslexic readers' naming speeds.

4.1 Cognitive processes involved in continuous and discrete RAN

Of the Rapid Automatised Naming (RAN) format variations, *continuous* tasks (items presented in a serial list) are generally found to be the most consistent predictors of reading ability, and consistently discriminate task performance for dyslexic and non-dyslexic groups compared with *discrete* tasks (items presented individually) (see Denckla & Cutting, 1999, for a review). This is often taken as evidence that the increased number of processes in serial naming tasks represent a 'microcosm' of the processes required for fluent reading (Wolf & Bowers, 1999).

Continuous formats are the original formats used by Denckla and Rudel (1976a, b). In this format, items are presented in a 10 x 5 matrix, and the participant is required to name the items from left to right as quickly as possible, starting with the top left-hand letter and finishing with the bottom right-hand letter. In Chapter 2, we reviewed the evidence showing that this version of RAN is a consistent predictor of reading ability (e.g., Blachman, 1984; Stanovich, 1981; Vellutino et al., 1996; Wagner, Torgesen, & Rashotte, 1994; Wolf, Bally, & Morris, 1986). At a relatively early point in naming-speed research, however, a debate emerged over whether performance on the RAN would still predict reading ability if a discrete format were used. The discrete format involves individual presentation of RAN items in a constant location. It therefore represents a less complex task, in which visual processing and retrieval of only a single item is required. Using this format, it is therefore possible to remove extraneous processing requirements involved in the continuous RAN, such as visual *scanning* and *sequencing* of multiple items (Wolf, 1991, p.128). Advocates of continuous formats argue, however, that it is precisely these additional processes that make RAN a consistent predictor of reading fluency.

This prediction is verified by empirical evidence: continuous list formats consistently predict reading ability, but discrete formats yield mixed results. Discrete naming tasks are found to discriminate good and poor readers (Bowers & Swanson, 1991; Nicolson & Fawcett, 1994). Bowers and Swanson (1991) demonstrated, however, that when latencies on discrete naming tasks were entered first into a regression equation, performance on continuous tasks contributed unique variance to reading ability beyond that explained by the discrete tasks. Thus, the authors concluded that the additional processing requirements (in addition to retrieval of the item's name) involved in continuous formats are closely related to reading ability. 'Pure' retrieval of individual items is not therefore sufficient to explain the RAN's relationship to reading. Other studies have found that discrete RAN tasks do not discriminate good and poor reading groups (e.g., Perfetti et al., 1978; Stanovich, 1981). Wolf and Bowers (1999) suggest that the success of discrete trials in discriminating reading groups depends on the severity of deficits in the poor reading group: severely disabled readers are more likely to have 'pure' naming problems in addition to fluency-related deficits associated with continuous naming tasks.

4.2 Which processes underlie scanning and sequencing behaviour?

Fluent reading requires rapid retrieval of the appropriate phonological codes for lexical items. As noted by Wolf and Bowers (1999), however, it also requires simultaneous processes, such as visual scanning and sequencing multiple lexical items. Whilst discrete versions of RAN therefore mimic retrieval of phonological codes, they do not demand the additional processes required during fluent reading. In contrast, continuous formats involve saccadic eye movements and sequential processing of each item in turn, which is arguably a more accurate reflection of the processes involved in fluent reading (Denckla & Cutting, 1999). Further, the additional processes involved in continuous RAN formats and fluency can be viewed as *extra*-phonological factors. That is, they cannot easily be explained by phonological processes. I now turn to an examination of the processes underlying these extra-phonological processes and how they might influence RAN performance and reading fluency.

4.2.1 Visual scanning

When we read, we make rapid eye movements with velocities as high as 500° per second. When the eye fixates an area of text, the duration of the fixation typically lasts only 200-300 ms (see Rayner, 1998). Precise oculomotor control (similar to the requirements when reading text) is also necessary to visually scan the continuous RAN array. Average readers accomplish this feat relatively automatically, but Stein and colleagues claim that aberrant eye-movements and fixations in dyslexic readers may mediate their difficulty in learning to read (Stein, 2003; Stein & Talcott, 2001; Stein & Walsh, 1997): in normally functioning readers, the magnocellular system is dominant in directing eye-movements and stabilising brief fixations made on words. Stein reasons that if the magnocellular system is impaired, oculomotor control is reduced, leading to poor control of eye-movements and unstable fixations. As a result, the information gleaned during fixation times is less than optimal, leading to reports of blurring and text migration from some dyslexic readers (e.g., Stein, 2003). In the RAN, this would lead to slower RTs when naming items in the array.

Support for poor oculomotor control in dyslexia was found in a study by Biscaldi, Gezeck, and Stuhr (1998), in which a correlation was found between abnormal saccadic control and reading ability. Specifically, the mean saccadic reaction times and the number of late saccades in response to single and sequential target items were significantly higher in the dyslexic groups. The authors suggest that the difficulties exhibited by the dyslexic groups are due to bottom-up anomalies in magnocellular function, causing impaired saccadic behaviour. However, a recent eye-tracking study by Hutzler, Kronbacher, Jacobs, and Wimmer (2006) found evidence to the contrary: eye movements to strings of consonants were not impaired relative to unimpaired readers (replicating a similar study by Olson, Conners, & Rack, 1991), and no relationship was found between tests of magnocellular function, such as coherent motion detection, and string processing. Hutzler et al. conclude that dyslexic readers' eye-movements are not themselves impaired, but reflect cognitive difficulties in processing the text itself. The literature therefore yields conflicting results concerning a causal role for abnormal eye movements in dyslexia.

4.2.2 Sequencing

Fluent reading involves sequencing visually presented lexical items within sentences and paragraphs, and in the continuous RAN, this process is represented by the requirement of naming successive letters in the correct order. In order to accomplish this, each item must be distinguished from surrounding items. Using a range of linguistic and non-linguistic tasks, a number of studies demonstrate that dyslexic readers require longer processing times and make a significant number of errors when sequencing items.

A recent study by Hawelka and Wimmer (2005) required participants to verbally identify one element in a multi-element array (one digit amongst a number of other digits). Although the digit-string task involves identification of a single target rather than naming a whole array of items, as in the RAN, both tasks involve distinguishing one item from a number of others. The results showed that for 2-digit strings, dyslexic readers required similar low presentation times to accurately identify the target item (~20ms). With longer digit strings, however, (4-6 digits), dyslexic readers' threshold times were significantly higher than for a group of average readers. Further, the threshold times for longer digit strings were reliably associated with the number of fixations made during word and pseudoword reading tasks. Similar group performances on 2-digit arrays led the authors to conclude that visual processing of stimulus features *per se* is not impaired in dyslexia. A deficit is only manifest when multiple items are presented simultaneously. A regression analysis also revealed that performance on the digits task contributed to the number of eye movements made during word reading independently from phonological measures, suggesting that multi-element processing affects reading independently of phonological processes.

Whilst the authors concede that the results can be interpreted in terms of the short-term maintenance of names for these multiple objects, findings from other studies using non-verbal tasks support a visual interpretation of the data. Visser, Boden, and Giaschi (2004), for example, demonstrated a visual sequencing impairment using the attentional blink (AB) paradigm. The AB requires participants to identify, detect or classify the second of two targets presented in rapid succession, and is considered a measure of the rapidity with which attention can be reallocated from the first to the second target. Thus, rapid disengagement from one stimulus to the next required in the task reflects the processes required for fluent reading. In this study, dyslexic readers were impaired at identifying the second target relative to unimpaired readers when the second target was in a different location from the first. The results are taken as evidence of impaired ability in the dyslexic group to shift visual attention from one item to the next. This conclusion is similar to Wolf and Bowers' (1999) hypothesis that continuous RAN formats reflect dyslexic readers' impaired ability to disengage from an already-named item in order to begin processing the next. Visser et al. discuss the potential relevance of their results to RAN processing, and suggest that dyslexic performance on the AB task may reflect a slice of the processes required in RAN. They acknowledge, however, that this claim is speculative given the different processes required in the RAN compared with AB.

A number of experiments by Pammer and colleagues using the *symbols* task (described in Chapter 2) also suggest visual attention deficits. Using non-alphabetic, letter-like symbol strings, Pammer, Lavis, Hansen, and Cornelissen (2004b) found that children with dyslexia were less accurate in recalling the correct sequence of symbols than unimpaired children, following a 110ms delay. This finding was also found to be robust with adult participants (Pammer, Lavis, Cooper, Lavis, & Cornelissen, 2005), and suggests that visual attention hampers accurate encoding of the relative positions of letters within words. However, a recent study by Hawelka, Huber, and Wimmer (2006) suggests that item position information *is* encoded by dyslexic readers. Hawelka et al. showed that dyslexic, as well as non-dyslexic readers demonstrate an advantage for first, centre and final letter positions. The dyslexic group required longer presentation threshold in order to demonstrate this advantage, however.

Pammer and Vidyasagar (2005) suggest that visual attention deficits are caused by impaired dorsal stream functioning. The dorsal stream - dubbed the "attentional spotlight" - receives most of its input from magnocells, and is responsible for guiding visual attention when reading (Pammer & Vidyasagar, 2005). Impaired dorsal functioning would therefore imply reduced ability to focus attention on the salient aspects of print when reading. Whitney and Cornelissen (2005) also propose that letter-identification errors occur because dispersed (non-serial) allocation of visual attention leads to reduced ability to discriminate a target item from the surrounding information. Perceptual analysis of the target stimulus might therefore be disrupted in dyslexic readers if too much attention is allocated to parafoveal items (items flanking the target area), reducing the attentional capacity available to process target items (items currently being fixated). A number of empirical studies support the proposal that dyslexia reflects a more parallel distribution of attention in the visual field than is found in non-dyslexic readers. Geiger and colleagues, for example, find that child and adult dyslexic readers are better at identifying items presented in the periphery than non-dyslexic readers, suggesting that dyslexic readers have a broader distribution of attention across the visual field (Geiger & Lettvin, 1987; Geiger, Lettvin, & Fahler, 1994; Lorusso et al., 2004; see also Facoetti et al., 2000). This has implications for their ability to sequence words when reading, and corroborates anecdotal reports from dyslexic readers that they "cannot see what is first and second" (Geiger, 1997).

The relevance of these findings to naming speed is that a parallel processing strategy resulting from visual attention impairments has potential implications for sequencing multiple items in the RAN. That is, focusing on the current item may be problematic if competing information on the *next* item is also activated in the parafovea. Preliminary uptake of orthographic and phonological information is a normal characteristic of reading behaviour (e.g., Miellet & Sparrow, 2004). However, studies suggest that dyslexic readers' parafoveal processing is impaired (Bouma & Leigen, 1977, 1980; Goolkasian & King, 1990; Klein, Berry, Briand, D'entremont, & Farmer, 1990; Pernet, Valdois, Celsis & Demonet, 2006), a subject to which we will return in Chapters 6 and 7.

It should also be considered that impaired processing of multiple items does not necessarily reflect a visual deficit, however. The multi-componential processes required in continuous versions of RAN may tax dyslexic readers' difficulties in performing more than one task simultaneously (e.g., Nicolson & Fawcett, 1990). If rapid activation and integration of visual and phonological information is not automatised, for example, the RAN task may tax limited executive processes to a greater extent than in skilled readers (Wolf & Bowers, 1999). Along similar lines, Breznitz (2003) suggests that dyslexic RAN performance may reflect asynchronous processing of visual and phonological information rather than a deficit in visual processing or phonological retrieval *per se*. In the current experiment, we investigate whether the *extra*-phonological processes required by RAN influence RAN performance and the RAN deficit in dyslexia. Evidence of an extra-phonological influence will support Wolf and Bower's (1999) proposal that reading fluency (as indexed by RAN) is underpinned by multiple processes, of which phonological retrieval is but one.

Experiment 1

Reading group differences on variations of the RAN format

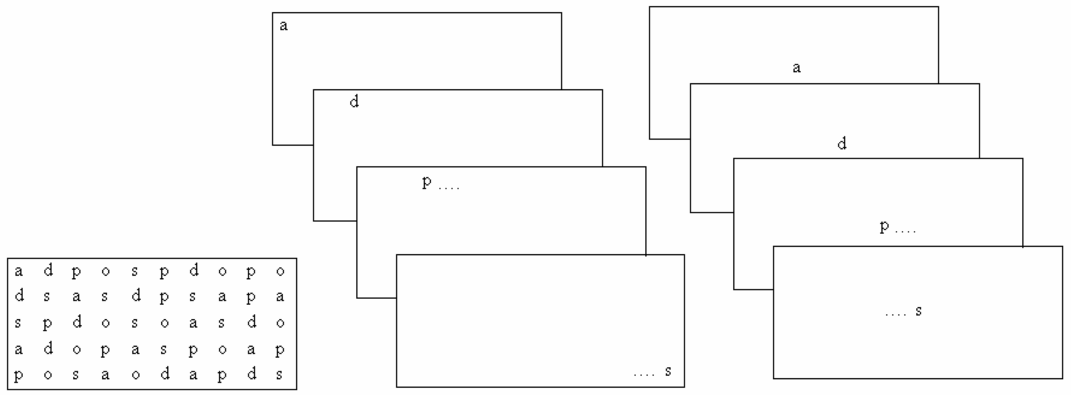
4.3 Rationale and predictions:

Studies using RAN to investigate the low-level processes implicated in reading fluency have relied on regression analysis (Blachman, 1984; Cornwall, 1992; Felton and Brown, 1990; Goldberg, Wolf, Cirino, Morris, & Lovett, 1998; Mann, 1984; Wimmer, 1993) and reading group comparisons on single task formats (e.g.

Berninger 1995; Denckla & Rudel, 1976 a, b; Wolff, Michel et al. 1990). Reading group comparisons to date have been informative in demonstrating longer RTs for dyslexic readers compared with non-dyslexic readers indicating impaired retrieval on RAN tasks, reflecting the disfluent reading rates characteristic of dyslexia. However, a direct comparison of dyslexic and non-dyslexic reading groups on continuous versus discrete RAN formats would indicate whether processes other than phonological retrieval influence RTs differentially for dyslexic and unimpaired groups. That is, how does the necessity to scan and sequence items influence RTs? And is this effect similar or different across reading groups? Evidence for an influence of scanning and sequencing on RAN would suggest that these low-level processes also exert an influence on reading fluency.

Experiment 1 involved a direct comparison of dyslexic and non-dyslexic reading groups on manipulations of RAN that tax different processing requirements. In addition to a comparison of continuous and discrete formats, it included a novel task format; measuring visual scanning independently of sequencing ability. To accomplish this, the format included a compromise between the discrete measure, in which items were presented individually, whilst preserving the *grid* format of the continuous list: items were presented individually, but the position of each successive item was analogous to the item positions used in the continuous format. Whilst this new format included visual scanning elements as well as graphemic access, presenting items individually removed the necessity of sequencing multiple items. In order to acknowledge the processes involved in each of the three RAN formats, the continuous version was renamed the *continuous-matrix*, whilst the discrete was termed *discrete-static*. The new format was labelled *discrete-matrix* to signify its compromise between the existing task formats (See Figure 5).

Figure 5: The RAN formats: continuous-matrix; discrete-matrix and discrete-static.



Continuous-matrix **Discrete-matrix** **Discrete-static**

Experiment 1 therefore comprised three RAN variations that segregated different task processes. The continuous-matrix version represented the original RAN in all its complexity. As such, it involved access to the grapheme of each individual item in addition to visual scanning and sequencing of multiple items. The discrete-static format presented letters individually in a single screen location. This format therefore implicated graphemic access with no extraneous influence from visual scanning or sequencing items. The novel discrete-matrix version involved individually presented letters but in positions analogous to the continuous matrix; preserving graphemic access and visual scanning task requirements, but removing the task sequencing element (the possibility of processing multiple items simultaneously) (see Table 1).

Table 1: Processes involved in the three variations of RAN formats. ● signifies a specific processing requirement.

Process	Continuous-matrix	Discrete-matrix	Discrete-static
Graphemic access	●	●	●
Oculomotor control	●	●	
Sequencing	●		

We predicted that if dyslexic readers' performance is mediated by impaired name retrieval, the dyslexic group should be consistently slower than the unimpaired group across presentation formats. If performance is also mediated by scanning and sequencing ability, however, the dyslexic group's performance should be relatively more impaired in some presentation formats than in others. Specifically, if dyslexic readers experience difficulty in making appropriate saccadic eye-movements, their performance should be particularly impaired in the continuous-matrix and discrete-matrix conditions compared to the discrete-static condition. Alternatively, if dyslexic readers experience difficulty only in parafoveal processing, their performance should be particularly impaired in the continuous-matrix condition relative to the two other conditions.

4.4 Method

4.4.1 Participants

A group of 21 young adults with dyslexia, and a group of 21 unimpaired adults participated in this study. Both reading groups comprised 10 males and 11 females. The mean difference in age between the two reading groups was not significant (dyslexic group: 22 years and 7 months (*SD* = 2.41); unimpaired group: 20 years and 7 months (*SD* = 3.32); $t = .36$; $p = .71$). Participants in both groups were native speakers of English with normal or corrected vision, and reported no other known linguistic or behavioural disorder. Participants in the dyslexic group were formally diagnosed with dyslexia, either at school age, by an educational psychologist, or by the University of Edinburgh Disability office. Participants were recruited by advertisement and were paid for their participation.

4.4.2 Materials and Design

4.4.2.1 Cognitive and literacy tests

In order to ensure valid differences between reading group abilities, a series of cognitive tests was administered. Each test measured an ability that has previously been associated with characteristics of dyslexia: spelling and word recognition tests

(Wide Range Achievement Test [WRAT-3]; Wilkinson, 1993) were administered in addition to 45 items from a non-word reading test measuring phonological decoding (Patient Assessment Training System (PATSy) battery; Lum, Cox, Kilgour, Snowling, & Haywood, 2005; see Appendix A). In order to test short term and working memory spans, forwards and backwards digit spans were taken from the Bangor Dyslexia Test (Miles, 1993).

4.4.2.2 Experiment

The experiment comprised three variant presentation methods of the standard RAN test, using the letters *a*, *s*, *d*, *p*, *o* from the original RAN (Denckla and Rudel, 1976b). In the *Continuous-matrix condition*, all letters were simultaneously visible in a continuous 10 x 5 matrix (per trial), in accordance with the standard RAN procedure. In the *Discrete-matrix condition*, individual letters were presented serially in matrix format, whilst in the *Discrete-static condition*, individual letters were presented serially in a single centred position. This resulted in a 2 (Group: dyslexic; non-dyslexic) x 3 (Format: continuous-matrix; discrete-matrix; discrete-static) design.

4.4.3 Procedure

4.4.3.1 Cognitive and literacy tests

Participants completed the WRAT-3 word reading and spelling sections in addition to forwards and backwards digit recall tests. This was followed by the non-word naming task. Words were presented in black print (Arial font 12) on an off-white background on a PC using the programme E-prime at a distance of 60cm. Participants were asked to name each item into a microphone, which was connected to a voice activated relay. 2000 ms after each item’s onset had been uttered, the word disappeared from the screen and was replaced by the next item. In all, the cognitive tests took approximately 30 minutes to administer.

4.4.3.2 Experiment

In the main experiment, participants were seated at a 60cm distance from a 15” RM monitor. Letters were presented in Arial 18 point font at 1° viewing distance in black type on a white background. In the two discrete conditions, a voice-activated relay (via microphone) removed the current letter and triggered presentation of the next letter, with an ISI of 0ms. The current letter disappeared from the screen at the onset of its pronunciation, and the time between initial presentation and voice onset was taken as the RT for each item. The last stimulus of each trial (50th letter) had inverse colors (white type on a black background) to signify that a keyboard response was required to end the trial. This applied to every condition. In the continuous-matrix condition, letters were presented with a 2° distance between each item. Participants were given a two-trial practice in each condition before the experimental session commenced. The experiment was blocked by condition and counterbalanced across participants. Each block comprised 4 trials, each comprising 50 randomised presentations of the 5 letters, and the session lasted approximately 20 minutes in total.

4.5 Results

4.5.1 Cognitive and literacy tests

Although dyslexic readers scored within the normal range (reflecting their status as high-functioning, dyslexic readers), they obtained reliably lower standardised scores than non-dyslexics on spelling and word reading sections of the WRAT-3 (Table 2) than the non-dyslexic group. They also obtained lower scores on non-word reading (error count) and backwards digit span than the non-dyslexic group. In this experiment, three members of the dyslexic group yielded an average RAN latency (across all conditions) that was lower than 1.5 SD above the non-dyslexic mean average RAN latency. They demonstrated impaired performance on the non-word naming test, however, (errors 1.5 SD above the non-dyslexic mean) and were not therefore excluded from the analysis.

Table 2: Reading group standardised scores on measures of spelling and word reading

		Dyslexic	Non-dyslexic	*t*	Cohen's *d*
Spelling	Mean	103.8	116.3	4.67**	1.43
	SD	10.02	7.2		
Word Reading	Mean	105.5	119.6	4.68**	1.44
	SD	12.6	5.6		
Non-word Reading	Mean	9.33	2.76	-4.14**	1.33
	SD	6.49	2.58		
Forwards Digit Span	Mean	9.71	10.90	1.48	-.057
	SD	2.31	1.84		
Backwards Digit Span	Mean	3.71	4.61	2.04*	-.052
	SD	2.00	1.43		

Note. $^*p < .01$; $^{**} p < .001$; Spelling and Word reading = standardised scores. Non-word reading = errors /44. Forwards digit span = /12; Backwards digit span = /6 points.

4.5.2 Reaction times

We calculated the mean participant RT (ms) to complete all trials in each condition. Scores that were 3 SDs above or below the Group mean were not included in the analysis. We decided on this, rather than a more stringent criterion to allow for the large variance in individual naming times, particularly in the dyslexic group. A summary of mean and standard deviation scores are included in Table 3:

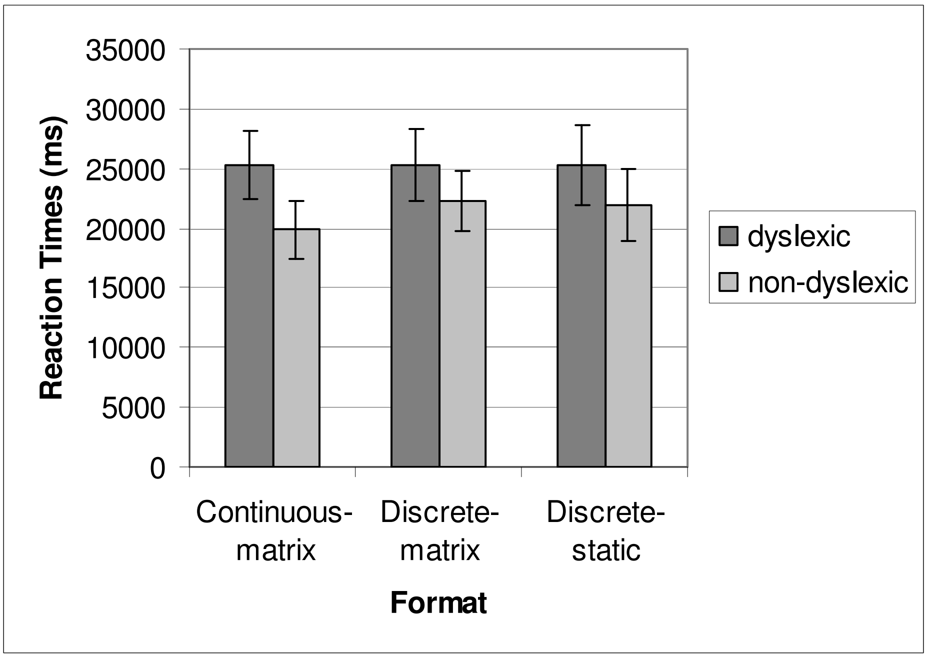
Table 3: Group mean latencies (ms) and standard deviations across the Format condition.

Group	Continuous-Matrix	Discrete-Matrix	Discrete-Static
Non-dyslexic			
Mean per trial\letter	19854 \ 397 (3015)	22261 \ 445 (2549)	21870 \ 437 (2497)
Dyslexic			
Mean per trial\letter	25261 \ 505 (3299)	25299 \ 505 (2947)	25301 \ 506 (2841)

To ensure that data between the continuous-lists and discrete-trials were compatible for analysis, a sum of reaction times across each trial was obtained. A two-way mixed-design ANOVA with the factors Group (dyslexic, non-dyslexic) and Format (continuous-matrix, discrete-matrix, discrete-static) revealed a main effect of

Group (*F* (1, 40) = 29.08, *p*<.01, η^2 = .42): The dyslexic group responded more slowly than the non-dyslexic reading group. The main effect of Format (*F* (2, 80) = 4.6, *p*<.05, η^2 = .10) and Group x Format interaction (*F* (2, 80) = 4.3, *p*<.05, η^2 = .09) indicated that group performance across the different conditions was not uniform. One-way ANOVAs over each level of the Group factor revealed a significant effect for the non-dyslexic group, (*F* (2, 40) = 9.579, *p*<.01, η^2 = .32), but no significant effects for the dyslexic group (*F* = .003*, p* = .99). Relative to their latencies in the discrete-static condition, non-dyslexic readers' performance did not significantly differ in the discrete-matrix condition (*t* = 1.33, *p* = 1.9), but RTs were significantly faster in the continuous-matrix condition, (*t* = -3.09, *df* = 20, *p* <.01). The dyslexic group's latencies did not differ significantly across different formats, however. (See Figure 6).

Figure 6: Mean RTs by group and presentation format (standard deviations denoted by error bars).



4.6 Discussion

In Experiment 1, our aim was to manipulate the RAN format in order to elucidate the role of low-level, extra-phonological processes in reading fluency. The number of processes involved in RAN was manipulated using different task formats. Previous studies suggest that the continuous RAN is a better reflection of reading fluency than discrete formats. This is taken as evidence that the additional processes involved in the continuous RAN (visual scanning and sequencing) simulate the processes required for fluent text reading. The aim of Experiment 1 was to investigate precisely how groups of dyslexic and non-dyslexic readers differ in terms of RT on continuous formats relative to the simpler discrete version. A new task format containing elements of continuous and discrete formats segregated the influence of visual scanning from sequencing.

First, our results demonstrated significant group differences across each task format. Although discrete formats do not consistently discriminate dyslexic from non-dyslexic readers (e.g., Perfetti et al., 1978; Stanovich, 1981), this experiment demonstrated a surprisingly robust group effect in the discrete-static condition, despite our high-functioning dyslexic sample. The results suggest, therefore, that the dyslexic sample in this experiment included readers with severe naming deficits (Wolf & Bowers, 1999). We cannot speculate from these results whether the discrete naming difficulties stemmed from attentional, visual or phonological difficulties in processing individual letter items, however.

Second, we found no evidence of impaired oculomotor control in this experiment: despite demonstrating longer latencies overall than non-dyslexics, dyslexics readers' performance on the novel condition involving letters presented serially in discrete positions was comparable to their performance for letters presented in a single position. Using the RAN paradigm, we did not, therefore, replicate results suggesting impaired oculomotor control in dyslexia (Biscaldi et al., 1998). Rather, our findings from RAN corroborate recent results suggesting that oculomotor control *per se* is intact (Hutzler et al., 2005).

However, direct comparison of the discrete conditions with the continuous-matrix format identified a critical naming difference between the two groups: the availability of multiple visual items in the array was associated with shorter naming latencies in the non-dyslexic reading group, but not in the dyslexic group. In contrast with the non-dyslexic reading group, the dyslexic group in Experiment 1 showed no facilitation in the continuous-matrix condition, which differed from the other conditions only in its simultaneous presentation of all letter items. The presence of items surrounding the target does little to facilitate dyslexic naming speed, therefore, suggesting difficulty in allocating attention effectively over more than one stimulus at a time (e.g., Facoetti et al., 2000).

The results yield several possible extra-phonological explanations of naming-speed deficits related to sequencing. First, a visual attention deficit may cause dyslexic readers to allocate attention discretely to each item in turn. This scenario is similar to predictions by Valdois, Bosse, and Tainturier (2004, 2006) that dyslexic readers have difficulty processing more than one item simultaneously. Alternatively, it is possible that presentation of multiple items *does* facilitate dyslexic latencies to some extent, but target processing is hampered by interference from parafoveal items, negating any potential facilitatory effects (Hawelka et al., 2006; Pernet et al., 2006). In their computational model of word reading, for example, Whitney and Cornelissen (2005) predict that dyslexic readers operate a parallel, rather than a sequential reading strategy. As a result, sub-optimal levels of attention are allocated to target (currently being processed) and flanking (upcoming) letters within words, leading to confusion when identifying target letters. Third, the effect may be a more general inhibitory deficit in suppressing activation of upcoming and already-named items in the array (e.g. Hari et al., 2001).

The results of Experiment 1 identify letter sequencing as one of the main processes discriminating dyslexic and non-dyslexic groups on the RAN. It remains to be seen whether these processes are exclusive from phonological retrieval ability, however: Clarke et al., (2005) suggest that impaired retrieval of phonological codes usurps executive processes, leading to a secondary problem in processing multiple sources of information. It is possible, therefore, that what appear to be ‘extra’-phonological influences on RAN may in fact be caused by a primary phonological deficit.

Experiment 2 in the next chapter will therefore attempt to directly parse the influence of visual and phonological factors on RAN performance.

4.7 Chapter Summary

Experiment 1 investigated which processes involved in RAN influence dyslexic and non-dyslexic reading groups. Reading groups were compared on three versions of RAN variations; ranging from complex (continuous-matrix) to relatively simple (discrete-static) formats. Whilst dyslexic readers were impaired across all versions of the RAN, reading groups were particularly divergent on the continuous-matrix: non-dyslexic readers appeared to make use of the additional information provided in the array, whereas dyslexic readers, for some reason, did not. This experiment therefore identified sequencing ability in the RAN as being a process that differentiates dyslexic from non-dyslexic reading groups, and provided a rationale for investigating sequencing in RAN in greater detail.

CHAPTER 5

Visual and phonological influences on fluency

5.0 Chapter Overview

In Chapter 4, we saw that naming speeds for non-dyslexic (but not dyslexic) readers are facilitated when multiple letter items are presented simultaneously. In this chapter, we investigate further the reasons for the reading group differences. Whereas Experiment 1 varied the task *format*, Experiment 2 also varied the RAN *content* (letter items) in order to tax visual or phonological processing. Regression analyses also investigated the contribution of discrete and continuous visual and phonological versions of RAN to word naming (exception and non-word) accuracy.

5.1 Dissecting the RAN

Manipulating the RAN format in Experiment 1 was useful for demonstrating that a) adult dyslexic readers are persistently slower at discrete naming and b) continuous tasks facilitate non-dyslexic but not dyslexic readers' naming speeds. Together, these findings suggest that when reading, non-dyslexic readers may take advantage of the multiple lexical items presented in a sentence to facilitate reading speed. This poses more of a difficulty for dyslexic readers, however.

This chapter further dissects the processes underlying these behaviours. Both reading text and naming in the RAN involve rapid attentional, visual and phonological processing in order to achieve fluent production of phonological codes, and each of these processing stages has been implicated in dyslexia. A deficit in either domain is therefore potentially implied in disfluent reading and the RAN deficit. In Chapter 4, for example, we reviewed a number of studies demonstrating that *visual* processing is impaired in dyslexia (e.g. Stein, 2003; Stein & Talcott, 2001; Stein & Walsh, 1997). Wagner et al. (1993) and Clarke et al. (2005), on the other hand, suggest that a primary *phonological* deficit usurps limited attentional resources, implicating slower latencies on the continuous RAN. There is also some evidence to suggest multi-modal processing-speed deficits in dyslexia (e.g., Fawcett & Nicolson, 1992; Nicolson & Fawcett, 1990) and Breznitz (2003) provides ERP data to suggest that RAN deficits reflect asynchronous integration of visual and phonological processes, rather than a deficit in any one mode of processing *per se*. The primary concern of this chapter is to investigate whether RAN is a measure of the speed with which letters can be visually identified, or the rapidity with which the letter name can be accessed. We also investigate whether difficulty in either of these processes might contribute to the naming-speed deficit characteristic of dyslexia. Second, we explore the contribution of visual and phonological processes involved in RAN to word reading.

5.2 Visual and phonological influences on RAN performance

Wolf and Bowers (1999) propose that performance on RAN tasks predicts reading ability because the complex interplay of processes involved in RAN mimics the processes required for fluent reading. In addition to phonological retrieval, therefore, their model predicts that attentional and visual processes influence RAN performance. However, RAN is still widely considered a measure of phonological retrieval (e.g., Clarke et al., 2005; Wagner et al., 1994). By creating variations of the RAN specifically designed to tap visual and phonological processes, it is possible to parse the influence of these processes on naming latencies.

Priming paradigms have been used in order to assess the influence of visual confusability on the letter naming process. Arguin and Bub (1995), for example, reported slower naming times when letters were primed with visually similar letters, but when primed with phonologically similar letters, there was no effect. This finding has been replicated by Compton (2003) within the RAN paradigm itself. In order to tax either visual or phonological processing stages, Compton varied the original RAN letter items (*a, s, d, p, o*) to include visually confusable items (*a, s, d, p, q*), phonologically confusable items (*a, s, d, p, v*) or both (*a, s, d, p, b*).

Although not explicitly discussed by Compton, there is a sound rationale for using these letter sets to investigate the processes underlying RAN and reading fluency. With reference to confusable rimes, it has long since been demonstrated that maintaining items with similar rimes in working memory is more difficult than maintaining phonologically unrelated items (Conrad, 1964; Hulme, 1984). Moreover, dyslexic readers' recall is impaired by similar rime items relative to age-matched controls (Johnston, Rugg, & Scott, 1987). Visually presented verbal material is re-coded via the articulatory loop into phonological information (Vallar & Baddeley, 1984), and although RAN does not tax the phonological short-term store capacity to the same extent as a recall task, if print information is recoded into phonological information, it should also be subject to confusability effects from similar rimes. Specifically, it is plausible that recent activation of rimes could hinder selection and production of similar rimes in the lexicon.

A similar rationale underlies the use of visually similar items for the purpose of promoting visual confusion. Studies demonstrate that short-term memory is influenced by visual similarity: Logie, Della Sala, Wynn, and Baddeley (2000) found poorer recall of visually similar items than visually distinct items. In a series of seminal studies, Bouma (1970) and Bouma and Liegen (1977, 1980) also showed that when the visual system is taxed (participants view letters at long distances, high eccentricities or flanked by other letters), lower-case letters tend to be confused with visually similar letters. This finding may reflect difficulty in selecting the appropriate orthographic code. Indeed, Badian (2005) demonstrated that poor readers have difficulty orienting orthographic items, and Berninger and colleagues suggest that an orthographic difficulty, along with phonological and morphological problems, are a core deficit in dyslexia (e.g., Richards et al., 2006). Bouma and colleagues interpret these findings in terms of impaired perceptual processing of visual information, however. A recent case study by Best and Howard (2005) also demonstrated that dyslexia involves substituting visually similar letter items for one another. In summary, therefore, there is evidence to suggest that similar phonological rime and visual information in RAN can influence non-dyslexic readers, but have a potentially stronger impact on dyslexic readers' latencies.

In the Compton (2003) study, the *visual*, *phonological* and *both* conditions were directly compared on an unselected sample of Grade 1 children and the value of these variants of RAN in predicting word reading was assessed 6 months later. Findings indicated that substituting one of the original items with a visually confusable item produced significantly shorter latencies compared with other RAN variants. However, the condition in which a visually and phonologically confusable letter was presented did not decrease latencies to a greater extent than that contributed by the visually confusable items. The findings therefore suggest that visual discrimination of letter forms during the RAN is an important component in determining performance levels.

However, the decrement in speed owing to the visually confusable RAN format was not uniquely associated with word reading skill development. Rather, the RAN version taxing *phonological* processes contributed unique variance to later word identification skill. The latter finding is perhaps not surprising, however, considering that phonological skill is found to contribute a significant amount of variance to word identification; particularly in young children (Torgesen, Wagner, & Rashotte, 1994). In the following section, we review evidence relating visual and phonological components of RAN to word reading ability.

5.3 The relationship between RAN and word reading

In Chapter 3, we outlined the substantial evidence from regression analysis suggesting that RAN performance contributes unique variance (beyond that accounted for by phonological skill) to reading outcome measures (e.g., Bowers, 1993, 1995; Bowers & Swanson, 1991; deJong & van der Leij, 1999; Kirby, Parrilla, & Pfeiffer, 2003; Manis, Doi, & Badha, 2000). Performance on the RAN is found to correlate with orthographic knowledge, and RAN predicts performance on orthographic choice tasks (Bowers et al., 1994; Manis et al., 1999). Orthographic knowledge is crucial for word recognition in languages such as English, in which irregular spellings necessitate the development of a lexical *sight vocabulary* (SV) (e.g., Harm & Seidenberg, 1999; Seidenberg & McClelland, 1989). Manis et al. (1999) showed that performance on the RAN was negatively correlated with exception (irregularly spelled) word naming accuracy. Exception word naming requires recall of orthographic word forms, and these results buttress evidence for a relationship between RAN and orthographic knowledge.

Wile and Borowsky (2004) went a step further to demonstrate that variations of RAN can index either sight vocabulary (SV) or phonemic decoding (PD) skill, depending on the task. In contrast with sight vocabulary, PD processing is a sub-lexical reading strategy, whereby each grapheme is sounded out according to its corresponding phoneme. Its representations are therefore based on phonological rather than orthographic properties of printed items. In order to tap SV and PD processes, Wile and Borowsky presented participants with the original RAN-Letters task (Denckla & Rudel, 1976) and a variation termed the RAN-LetterSounds task. Instead of retrieving the letter name, the RAN-LetterSounds required articulation of the letter sounds (e.g., the letter 'd' would require the pronunciation /d/ instead of /di/).

The authors predicted that whereas exception word naming accuracy would contribute unique variance to retrieval of letter names (to the RAN-Letters), but not to RAN-LetterSounds, phonemic decoding accuracy would predict performance on the new RAN-LetterSounds task, but not RAN-Letters. This double dissociation in the predictive value of SV and PD processes to different versions of RAN was borne out in regression analyses. Bowers et al. (1994) suggest that the relationship between performance on RAN-Letters and SV processing stems from the quality of lexical representations. That is, rapid access to the visual form of a letter required in RAN taps similar processes to retrieval of the lexical form of words. In the RAN-LetterSounds task, on the other hand, retrieval of the letter sound is analogous to accessing phonological representations required for decoding. As well as corroborating previous correlations between RAN and exception word reading performance (e.g., Clarke et al., 2005; Manis et al., 1999), therefore, the RAN-LetterSounds task provides a within-task variant of RAN that allows comparison of

SV and PD processing (Wile & Borowsky, 2004).

These findings suggest that the processes required for high latencies on the RAN tap in to the processes required for whole word recognition, or sight-word vocabulary (SV) processing (Wile & Borowsky, 2004). Bowers et al. (1994) and Wolf and Bowers (1999) proposed that the automaticity with which the names of common items could be accessed in the RAN is indicative of how quickly the lexical representations of familiar words are accessed. Children who are slow at RAN are also slow at accessing letter codes, resulting in difficulty abstracting orthographic regularity from print. If a child is slow at identifying individual letters, for example, they will have reduced sensitivity to frequently occurring letter patterns within printed words. As a result, the child will develop underspecified memory representations of irregularly spelled words, leading to poor SV accuracy.

Performance on the RAN is therefore linked with the quality of orthographic recognition units for frequently encountered words. However, Wimmer and Mayringer (2002) found that some dyslexic children with slow serial reading maintained normal accuracy levels on spelling tasks. The authors suggested that some dyslexic readers experience difficulty in perceptual or attentional processing of letter strings as opposed to a problem in orthographic word recognition. Hawelka and Wimmer (2005) also found that when asked to verbally identify one of two elements the dyslexic group in their study obtained similar accuracy thresholds to average readers. When asked to identify one element in a multi-element array, however, dyslexic readers' accuracy levels decreased with a steeper function than average readers in response to an increase in the number of elements. These results suggest that processing individual orthographic properties is intact in dyslexia, and the visual system is only impaired when it is required to process multiple items. These findings buttress theories suggesting a visual deficit only in *complex* visual situations (Vidyasagar, 2004). Valdois, Bosse, and Tainturier (2004; 2006) also propose that dyslexic participants suffer from visual attentional disorder limiting the number of distinct elements that can be processed simultaneously. These findings introduce the possibility that low-level, multi-element visual processing in RAN fosters its relationship with word reading. Whilst Bowers et al. (1994) suggest a link between orthographic processing and SV skills, such as exception word reading, however, perceptual visual deficits have also been associated with impaired PD processes, such as non-word naming (Castles & Coltheart, 2004; Pammer, Lavis, Cooper, Hansen, & Cornelissen, 2005).

Experiment 2

The influence of visual and phonological processes on fluency

5.4 Rationale and predictions:

Studies using RAN to investigate the influence of visual and phonological processes on reading fluency suggest that visual processing exerts a significant influence on RAN performance. Of the existing studies manipulating letter information, the influence of these factors has only been assessed for average or unselected reading groups, and no study in the current literature has compared reading groups of dyslexic and average readers on variations of RAN designed to tap visual versus phonological processing. Experiment 2 therefore used a similar design to Compton (2003): A *visual* letter set, comprising the letters a, s, d, p, q was compared with a *phonological* letter set, consisting of a, s, d, p, v. Whereas p and q are visual reversals, p and v contain identical phonological rimes. These letter sets are therefore representative of visual and phonological confusability, respectively (Compton, 2003). In an extension of the Compton study, however, this experiment also included the different RAN format conditions involved in Experiment 1. Each Letter set was therefore presented across the *continuous-matrix*, the *discrete-matrix* and the *discrete-static* formats. This manipulation was included to replicate the results of Experiment 1, and to investigate the relative roles of visual and phonological processing in the context of multiple and individually presented letters. The final addition to Compton's study was to compare latencies for groups of dyslexic and non-dyslexic readers across Letter set and Format conditions. Experiment 2 therefore yielded a 2 (Letter sets visual; phonological) x 3 (Format:

continuous-matrix; discrete-matrix; discrete-static) x 2 (Group: dyslexic; non-dyslexic) mixed design.

We predicted that Experiment 2 would replicate the results of Experiment 1: The dyslexic group would demonstrate longer latencies overall, and only the non-dyslexic reading group would show facilitated latencies on the continuous-matrix format. We also predicted that the pattern of results across Letter sets would replicate those of Compton (2003); demonstrating longer latencies overall for the visually confusable letter sets. Having obtained baseline results in the non-dyslexic reading group, however, it was then possible to compare dyslexic readers' performance. If the naming-speed deficit characteristic of dyslexia reflects a visual or phonological deficit, a Group-by-Letter set interaction was expected, such that the dyslexic group would show higher latencies on the Letter set that reflected their processing difficulty.

A prediction was also made concerning the interaction of Letter sets with Format conditions across reading groups. Specifically, if the visual processing deficit in RAN involves visual attention over multiple items, but discrimination of individual items is preserved (e.g., Hawelka & Wimmer, 2005), we expected that dyslexic readers would show increased latencies in the visual Letter set only in the continuous-matrix Format condition.

In addition to these experimental comparisons, we investigated the variance contributed by visual and phonological RAN to measures of SV and PD processing skills (exception word naming and non-word decoding). Wile and Borowsky (2004) demonstrated that exception word reading ability (SV skill) predicted performance on the original RAN-Letters version, whilst pseudohomophone reading (PD skill) predicted latencies on the RAN-LetterSounds. A planned analysis in this study was to investigate whether a similar relationship could be elicited from visual and phonological versions of RAN. That is, we intended to investigate whether performance on the continuous format of the visual RAN predicted exception word reading and performance on the phonological RAN predicted non-word naming accuracy. Considering that these Letter sets differed only on one letter, however, it was possible that a very strong correlation between their performances would be found. If the correlation was found to be stronger than .9, then these variables would not be entered into the regression together (Wile & Borowsky, 2004, p. 53) and the analysis would not be conducted.

A further set of regression analyses investigated the amount of variance contributed by *continuous* versions of visual and phonological Letter sets when performance on discrete versions had been controlled (entered first into the model). Bowers and Swanson (1991) found that continuous versions of the RAN contributed independent variance to word reading over and above the variance contributed by discrete RAN trials. Moreover, Hawelka and Wimmer (2005) found that visual processing in dyslexia is impaired when the system is taxed by multiple items. By investigating the unique predictive value of continuous tasks, it was possible to test whether multiple visual item processing involved in RAN relates to processing multiple letters involved in word recognition. If, for example, the ability to process multiple letters is related to either exception or non-word reading, we could expect either visual or phonological (or both) continuous RAN conditions to predict unique variance to either of these measures. If, on the other hand, multiple item processing does not predict word reading accuracy, we expect that continuous formats will not contribute any additional unique variance.

Latency measures were used for the main analysis because RAN is thought to tap how rapidly an individual can identify and produce over-learned stimuli (see Chapters 2 and 3 for a discussion). Errors on the task should therefore be infrequent, but studies demonstrate that in young children, the general error rate is approximately 2% (Vellutino et al., 1996). Dyslexic groups tend to produce more errors than average reading groups (approximately 4%), however (Stanovich, 1981). In Experiment 2, we also investigated the error rate in an adult, high functioning (University student) population. If error rates are a function of speed-accuracy trade-off, we expected a negative correlation between naming latencies and error rates. If, however, slow naming is also indicative of high error rates, we expected a positive correlation between these measures.

5.5 Method

5.5.1 Participants

Twenty young native English speaking adults with dyslexia and 20 non-dyslexic reading students participated in this study. All participants were students recruited from the University of Edinburgh and Queen Margaret's University, Edinburgh. The mean age was 22 years and 4 months (*SD* = 4.72) for the dyslexic group and 20 years and 8 months (*SD* = 2.79) for the non-dyslexic reading group; with no significant difference between the two (*t* = .5; *n.s.*). The non-dyslexic reading group comprised 7 males compared with 9 males in the dyslexic group. Participants from the dyslexic group were formally diagnosed with dyslexia and verbally reported that they knew of no other linguistic or behavioural disorder that might confound their performance. Students were recruited using advertisements and were paid for their participation.

5.5.2 Materials and Design

5.5.2.1 Cognitive and literacy tests

The cognitive profile tests used in Experiment 1 to validate reading group membership were also used in Experiment 2: Spelling and word recognition tests (Wide Range Achievement Test [WRAT-3]; Wilkinson, 1993) and forwards and backwards digit spans were taken from the Bangor Dyslexia test (Miles, 1993). The non-word reading test administered in Experiment 1 (Patient Assessment Training System (PATSy) battery; Lum, Cox, Kilgour, Snowling, & Haywood, 2005; see Appendix A) was used in addition to a measure of exception word naming, which consisted of 45 items taken from Manis, Seidenberg, Doi, Chang, & Petersen (1996) (See Appendix B). This experiment also included a non-verbal IQ test (Ravens' Advanced Progressive Matrices; Set 1; Raven, Raven & Court, 1998) to ensure that there were no fundamental differences in non-verbal IQ between groups which may have biased interpretation of the data.

5.5.2.2 Experiment

As in Experiment 1, Experiment 2 comprised three variant presentation methods of the standard RAN test. In the *Continuous-matrix condition*, all letters were simultaneously visible in a continuous 10 x 3 matrix (per trial). In this experiment, each trial comprised 30 items, rather than 50, to avoid participant fatigue. In the *Discrete-matrix condition*, individual letters were presented serially in matrix format, whilst in the *Discrete-static condition*, individual letters were presented serially in a single centred position. Moreover, the original letters *a, s, d, p, o* were manipulated in this experiment: the factor Letter set included the levels *Visual*, comprising the letters *a, s, d, p, q* and *Phonological*, comprising the letters *a, s, d, p, v*. The two blocks (visual and phonological Letter sets) comprised 8 trials each (4 in each discrete and continuous condition), in which presentation of letters within each trial was randomised.

5.5.3 Procedure

5.5.3.1 Cognitive and literacy tests

Participants completed the WRAT-3 word reading and spelling sections in addition to forwards and backwards digit recall tests. This was followed by the exception and non-word naming tasks. Words were presented in black print (Arial font 12) on an off-white background on a PC using the programme E-prime at a distance of 60cm. Participants were asked to name each item into a microphone, which was connected to a voice activated relay. After the onset of each item had been uttered, the item remained on the screen for a further 2000 ms before being replaced by the next item. Exception and non-word tasks were presented according to a latin square design across participants. Set 1 of the Raven's progressive Matrices was also administered. In all, the cognitive tests took approximately 40 minutes to administer.

5.5.3.2 Experiment

For the main experiment, participants were seated at a 60cm distance from a 15" RM monitor. As in Experiment 1, letters were presented in Arial 18 point font at 1° viewing distance in black type on a white background, with a 2° viewing distance between each letter. In the two discrete conditions, a voice-activated relay (via microphone) removed the current letter and triggered presentation of the next letter, with an ISI of 0ms. The current letter was erased at the onset of its pronunciation, and the time between initial presentation and voice onset was taken as the RT for each item. The last stimulus of each trial (50th letter) had inverse colors (white type on a black background) to signify that a keyboard response was required to end the trial. This applied to every condition. In the continuous-matrix condition, letters were presented with a 2° distance between each item.

Participants were given a two-trial practice in each condition before the experimental session commenced. A Latin square design was used to counterbalance the format condition. Participants alternated on whether they began with the visual or phonological block of trials. The session lasted approximately 20 minutes in total.

5.6 Results

5.6.1 Cognitive and literacy tests

As in Experiment 1, dyslexic readers scored within the normal range (reflecting their status as high-functioning, dyslexic readers), but they obtained reliably lower standardised scores than non-dyslexics on spelling and word reading sections of the WRAT-3 (Table 3). They also obtained lower scores on non-word, and exception word naming (error count) and backwards digit span (see Table 4). Three members of the dyslexic group obtained overall average RAN latencies that were below 1.5 SD of the non-dyslexic mean. Two of these individuals demonstrated impaired performance (errors higher than 1SD of the non-dyslexic mean) on non-word naming. The third member of the dyslexic group obtained a mean latency above the non-dyslexic mean on non-word naming (but within 1SD). However, he also obtained a standardised score of more than 1.5 below the non-dyslexic mean on WRAT-spelling. Further, all three individuals obtained IQ scores that were in the same range as the non-dyslexic group (i.e. within 1 SD of the non-dyslexic mean). For these reasons, we did not exclude any participant data from this analysis.

Table 4: Reading group standardised scores on measures of spelling and word reading

		Dyslexic	Non-dyslexic	*t*	Cohen's *d*
Spelling	Mean	96.75	117.9	5.53**	-1.75
	SD	16.22	5.40		
Word reading	Mean	103.80	116.33	6.10**	-1.44
	SD	7.02	10.02		
Non-words	Mean	11.35	2.05	5.47**	1.73
	SD	7.37	1.88		
Exception words	Mean	4.80	1.00	4.03**	1.3
	SD	4.12	.086		
Forward digit span	Mean	9.55	10.26	.98	-.32
	SD	2.17	2.21		
Backwards digit span	Mean	3.67	4.84	2.25*	-.73
	SD	1.85	1.30		
Raven's APM	Mean	10.75	11.20	.27	-.35
	SD	1.40	1.15		

Note. *$p < .01$; ** $p < .001$; Spelling and Word reading = standardised scores. Non-word naming = errors /44. Exception word naming = errors / 45. Forwards digit span = /12; Backwards digit span = /6 points. IQ = /12.

5.6.2 Reaction times

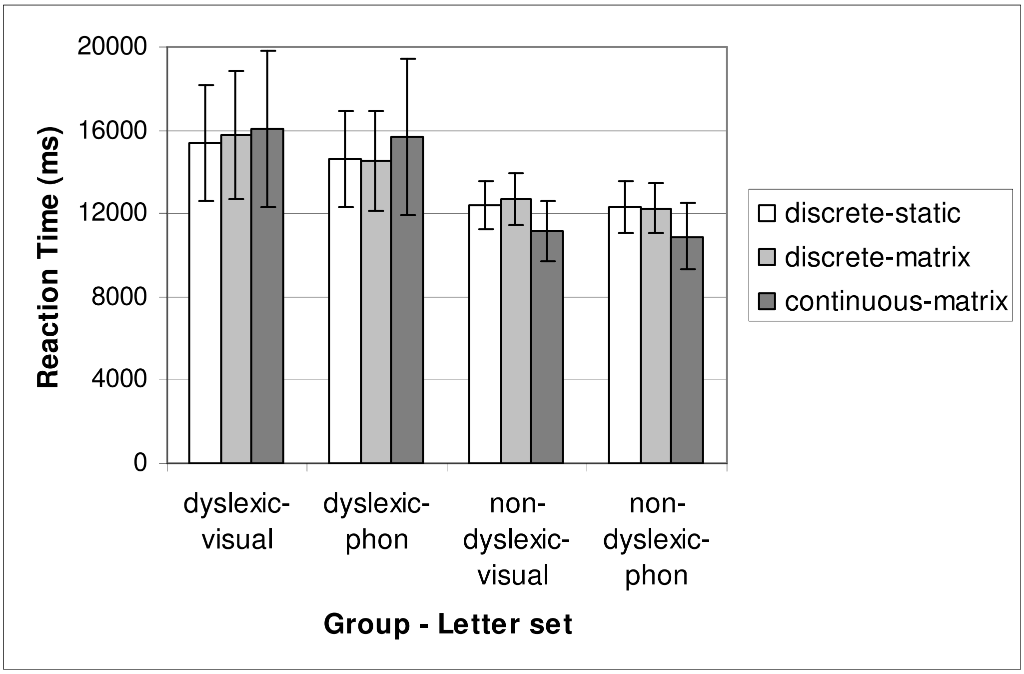
We calculated the mean participant RT (ms) to complete all trials in each condition (see Table 5 and Figure 7) and excluded data falling 3 SDs above or below the Group mean. To ensure that data between the continuous-lists and discrete-trials were compatible for analysis, a sum of reaction times across each trial was obtained. A three-way mixed-design ANOVA with the factors Group (dyslexic, non-dyslexic), Format (continuous-matrix, discrete-matrix, discrete-static) and Letter set (visual, phonological) demonstrated that in general, the dyslexic group yielded higher latencies than the non-dyslexic reading group (F (1, 38) = 34.05 = $p < .001$; η^2 = .44). We did not replicate the main effect of format found in Experiment 1 (F = .658, n.s.). The most likely explanation for this is that RTs in the two Letter sets behaved differently across different formats. The variance accounted for by Format was not, therefore, consistently in the same direction. As in Experiment 1, an interaction was found between Group and Format (F (2, 76) = 6.76, $p < .01$; η^2 = .15), such that the non-dyslexic reading group benefited from multiple item presentation in the continuous-matrix, but the dyslexic reading group did not. One-way ANOVAs for each Group supported this interpretation: the non-dyslexic group yielded significant effect across the Format conditions (*F* (1, 38) = 23.65, $p < .001$, $\eta^2 = .55$) whereas the dyslexic group yielded no significant effect (*F* = .95, *n.s.*).

A main effect of Letter set was also found (*F* (1, 34) = 13, $p < .01$; $\eta^2 = .26$): In general, Letter sets containing a visually confusable item implicated longer latencies for both reading groups. A marginal Group-by-Letter set interaction suggested that dyslexic readers were more impaired in the visual Letter sets than phonological sets; compared with dyslexic readers (*F* (1, 38) = 3.22, $p = .08$; $\eta^2 = .08$). A non-significant Format-by-Letter set interaction (*F* = 1.62, *n.s.*), however, suggested reading groups' higher latencies in visual Letter sets did not vary as a function of different presentation formats. A final prediction was that dyslexic readers might demonstrate higher latencies than non-dyslexic readers in a specific Format (e.g., the continuous-matrix condition). There was no significant Group-by-Format-by-Letter set interaction, however (*F* = .75, *n.s.*).

Table 5: Group means and standard deviation latencies (ms) across Letter set and Format RAN conditions.

Group	Visual			Phonological		
	Contin. Matrix	Discrete-Matrix	Discrete -Static	Contin. Matrix	Discrete-Matrix	Discrete -Static
Non-Dyslexic						
Mean per trial \letter	11138 (1427)	12688 (1258)	12400 (1128)	10906 (1604)	12252 (1176)	12281 (1235)
Dyslexic						
Mean per trial \letter	16010 (3750)	15751 (3065)	15416 (2798)	15655 (3723)	14513 (2432)	14660 (2306)

Figure 7: Group mean RTs and standard deviations across Letter set and Format conditions.



5.6.3 Regression

An initial correlation analysis revealed strong relationships between a number of the variables in this study (see Table 6). In particular, high collinearity (above .9) between visual and phonological versions of RAN precluded analyses investigating the relative variance contributed by visual and phonological formats on exception and non-word naming accuracy. Furthermore, high collinearity between discrete-static and discrete-matrix RAN formats meant that only discrete-static condition was entered into regression analyses. We chose the discrete-static condition (over the discrete-matrix) because it represents minimal complexity in RAN processes and serves as a contrast to the complexity demonstrated in the continuous matrix.

In choosing the discrete-static condition, we could ensure that correlations between word recognition measures and discrete RAN rely on recognition of the letter and access to the graphemic label, rather than additional factors, such as eye movements and sequencing.

Table 6: Correlations among experimental variables and word reading measures.

	Vis: d-s	Vis: d-m	Vis: c-m	Phon: d-s	Phon: d-m	Phon: c-m	Exc.
Vis: d-s							
Vis: d-m	.957**						
Vis: c-m	.585**	.610**					
Phon: d-s	.834**	.903**	.588**				
Phon: d-m	.908**	.920**	.537**	.911**			
Phon: c-m	.635**	.670**	.907**	.660**	.649**		
Exc.	.584**	.498**	.334*	.419**	.542**	.468**	
Non-w.	.671**	.542**	.528**	.462**	.604**	.630**	.834**

Note: ** = p < .01; d-s = discrete-static; d-m = discrete-matrix; c-m = continuous-matrix.

Four stepwise regression analyses were conducted in order to investigate how much additional variance is contributed to word reading by continuous versions of RAN. Dependent measures in each analysis comprised either exception word or non-word naming. For each dependent variable, two separate analyses were conducted. The first analysis involved variations on the RAN format in the *visual* Letter set, and the second analysis investigated the variance contributed by the equivalent formats in the phonological condition. The discrete-static condition was entered first into the equation, followed by the continuous-matrix condition. If the additional processing requirements involved in the continuous matrix contribute to word naming, we expected that the continuous-matrix condition would yield unique variance beyond that explained by the discrete-static condition.

Results are summarised in Tables 7 and 8. The discrete-static condition contributed significant variance to both exception word and non-word naming accuracy (t = 3.58, p < .001; t = 3.76, p < .001). The continuous-matrix visual condition, however, did not contribute independent variance either to exception word accuracy (t = .064, *n.s.*), or non-word decoding accuracy (t = 1.41, p < n.s.).

Table 7: The contribution of discrete-static, discrete-matrix, and continuous-matrix visual versions of RAN to variance in exception and non-word naming accuracy.

Variable	*B*	*SE B*	*Β*	*R²*
Exception words				.341
Constant	-8.042	2.567		
Visual: discrete-static	.001	.000	.590	
Visual: continuous-matrix	.000	.000	-.010	
Non-words				.479
Constant	-19.508	4.639		
Visual: discrete-static	.002	.000	.550	
Visual: continuous-matrix	.000	.000	.207	

In the *phonological* RAN Letter set, the discrete-static condition did not contribute independent variance to exception word accuracy (t = 1.02, *n.s.*), but the continuous-matrix condition contributed marginally significant variance (t = 1.78, p =.083). Similarly, when regressed on non-word naming, the discrete-static condition did not contribute independent variance (t = .484, *n.s.*), but the continuous-matrix condition contributed unique variance (t = 3.4, p < .01) to this measure.

Table 8: The contribution of discrete-static, discrete-matrix, and continuous-matrix phonological versions of RAN to variance in exception and non-word naming accuracy.

Variable	*B*	*SE B*	*Β*	*R²*
Exception words				.241
Constant	-5.592	3.156		
Phon: discrete-static	.000	.000	.195	
Phon: continuous-matrix	.000	.000	.339	
Non-words				.401
Constant	-11.502	5.663		
Phon: discrete-static	.000	.001	.082	
Phon: continuous-matrix	.001	.000	.576	

The results of these analyses suggest that in the visual RAN, the processes involved in discrete versions contribute variance to word reading, but information from multiple letters contributes no additional variance. Conversely, in the phonological RAN, discrete items did not account for a significant amount of variance in exception and non-word naming, but multiple item presentation in the continuous-matrix condition contributed significant, independent variance to these measures.

5.6.4 Errors

An error count was obtained for participants across each RAN condition. An error included any articulated response that was an incorrect name for the target. Both non-dyslexic and dyslexic readers obtained error rates of approximately 1% across trials. Although the RT analyses above necessarily included these errors, the low number of errors for both groups renders it unlikely that errors influenced RTs to a large degree. A Kruskal-Wallis analysis with the factor Group demonstrated significant differences in the visual discrete and continuous conditions and in the phonological discrete and continuous conditions (Table 9). In addition to yielding slower latencies on these measures, therefore, the dyslexic group also produced more errors than non-dyslexic readers across conditions.

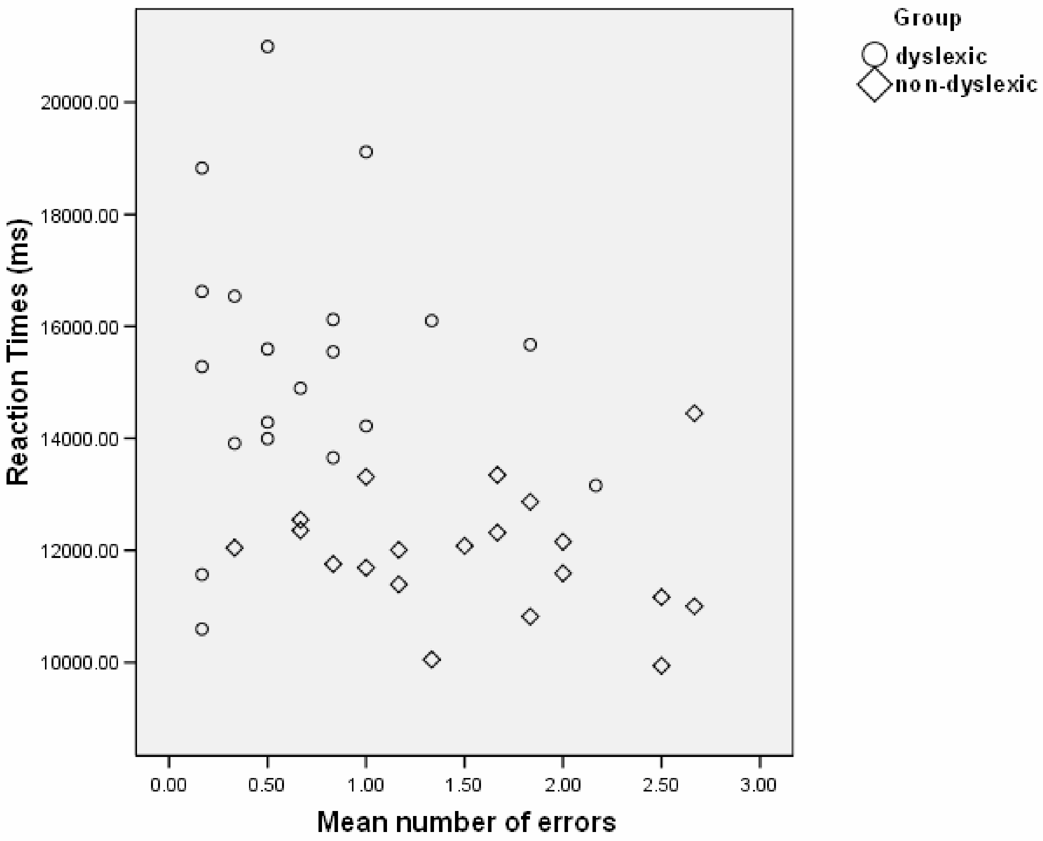
Table 9: Group error counts (averages and standard deviations) across Letter sets and Format conditions.

Group	Visual			Phonological		
	Discrete-Static	Discrete-Matrix	Continuous-Matrix	Discrete-Static	Discrete-Matrix	Continuous-Matrix
Non -dyslexic	0.40 (0.68)	1.15 (0.93)	0.50 (0.76)	0.90 (1.02)	0.80 (0.95)	0.45 (0.60
Dyslexic	1.45 (1.50)	1.60 (1.35)	1.11 (0.82)	1.65 (1.53)	1.94 (1.58)	1.67 (0.99)
χ^2	6.42*	1.04	5.87*	2.96	5.97*	13.15*

Note: * $p < .05$

A general mean latency and accuracy score was next calculated for each participant and a Pearson's coefficient test was conducted to investigate the relationship between these variables. Figure 8 depicts error rates as a function of latencies. A negative correlation between latency and accuracy scores was obtained: High latencies were significantly associated with a low error score (r = -.409 (40), $p < .01$). Despite higher error rates overall in the dyslexic group, therefore, a speed-accuracy trade-off was found in the RAN: overall, slower latencies were associated with higher accuracy levels.

Figure 8: The relationship between mean RAN latencies and the mean number of errors per participant.



5.7 Discussion

In Experiment 2, we used versions of the RAN to investigate the potential influence of visual and phonological processes on reading fluency. Visual and phonological processes involved in RAN were taxed using letters that were either visually or phonologically similar. Naming visually similar letters involved distinguishing visually similar features of both letters and matching this information to orthographic representations in the lexicon. Naming phonologically similar letters required selecting the appropriate phonological code from representations with similar rimes. In this experiment, visual and phonological letter set conditions were crossed with the RAN formats introduced in Experiment 1. Using these manipulations, we investigated whether taxing visual or phonological processes influenced naming speeds in both discrete and continuous formats of the RAN.

Results from the *Format* manipulation replicated findings from Experiment 1: Overall, the dyslexic group yielded longer naming latencies compared with the non-dyslexic group and a Group-by-Format interaction demonstrated that non-dyslexic, but not dyslexic readers' latencies were facilitated in continuous task formats. This finding again suggests that the availability of processing multiple items is advantageous to skilled readers. When reading text, for example, non-dyslexic readers may process more than one word simultaneously, which facilitates reading fluency. Replication of this result suggests that the effect found in Experiment 1 is robust. In contrast with Experiment 1, there was no main effect of Format, but this may in part be explained by differences in RTs in response to the different Letter sets introduced in Experiment 2: Although both letter sets behaved similarly across formats, there was some disparity between visual and phonological sets in the dyslexic group, in particular, which may have dampened the Format effect in this experiment.

With reference to the Letter sets, a main effect was found, demonstrating that both reading groups took longer on visually compared with phonologically confusable versions of the RAN. These results in a high-functioning adult population support previous findings by Compton (2003) demonstrating that an unselected sample of young children yielded longer latencies on visual letter sets than phonological letter sets. The current results suggest that the ability to discriminate the visual forms of letters influences RAN performance, and supports Bowers et al's claim that rapid access to the visual form of letters is an important predictor of RAN latencies.

Moreover, a marginal Group-by-Letter set interaction suggested that members of the dyslexic group obtained higher latencies than non-dyslexic readers on visual compared with phonological letter sets. Discriminating visually similar letters was, therefore, particularly difficult for dyslexic readers in the RAN and may contribute to impaired fluency rates when reading. In addition to supporting predictions by Wolf and Bowers (1999) that a deficit in automatising lexicalised stimuli stems from domains other than phonology, these group comparisons build on recent findings from a single case study (Best & Howard, 2005) demonstrating high rates of visual confusion in a dyslexic reader. Best and Howard suggested that high rates of visual error in dyslexia is one symptom of an over-reliance on visual codes when processing written material. Whereas normal readers tend to re-code written verbal information into phonological form (e.g., Vallar & Baddeley, 1984), they suggest that dyslexic readers rely more on visual processes to compensate for their phonological difficulty. This explanation is similar to Snowling and Hulme (1989)'s conceptualisation of the compensation strategies used by dyslexic readers, but it does not clearly explain why dyslexic readers should have *difficulty* with visually similar items. If anything, a system that has been over-used as a compensation strategy should be stronger than in non-dyslexic readers leading to less visual confusion.

The results show that visually similar letters taxed dyslexic readers' pre-existing deficit in rapidly processing or accessing letter forms during the RAN. Our findings suggest, therefore, that low-level visual processing may be a key factor in determining the development of fluent reading: When the visual system is impaired (whether directly – e.g., a magnocellular deficit – or indirectly, as a result of a domain general deficit), fluency rates become slower. An additional prediction investigated the nature of this deficit. If a visual difficulty reflects impaired processing of multiple items (Hawelka & Wimmer, 2005; Valdois et al., 2004, 2006; Vidyasagar, 2004) but visual processing and orthographic matching on the individual letter level is intact, then the dyslexic group would be significantly slower than non-dyslexic readers in the continuous-format of the visual Letter set. This experiment did not yield a Group-by-Letterset-by-Format interaction, however, suggesting that the visual difficulty demonstrated in the dyslexic group was not specific to multiple item processing. Discriminating between two visually similar letters in the discrete format was therefore comparable with discriminating letters in the continuous format.

It is unlikely, however, that the visual RAN Letter set in this experiment was taxing perceptual processes. The experimental design involved random order of letters (similar to the Compton (2003) design), with the effect that confusable items in the continuous-matrix rarely juxtaposed each other. Instead, it is probably the case that increased latencies in the visual confusable conditions were due to activated memory representations of items similar to the letter currently being named. In this experiment, recent activation of a similar letter form to the target item (currently being named) interfered with matching the target's features to stored orthographic representations. The current experiment cannot elucidate why the effect of visually similar items was stronger in the dyslexic group, however. It is possible that the finding reflects a specific impairment in establishing orthographic representations. Alternatively, degraded orthographic representations may be the result of a difficulty in perceptual or attentional processing of visual information (e.g., Thomson et al., 2005).

Random presentation of confusable items in the array may also explain why the Group-by-Letter set interaction was only marginal in this experiment. Whilst memory activation of confusable items was clearly enough to cause a marginal effect, perhaps a stronger effect may have been found in circumstances which allowed direct perceptual comparison of visual and phonological similarity. For example, had confusable letters been presented successively, we would expect that the interference between them would have been stronger. Two confusable items might yield stronger interference because memory activation of the first item would be more recent when naming the second item. In addition, when naming the first item some perceptual interference from the second item might be expected from the parafovea.

The regression analyses in this study focused on the extent to which presentation of multiple letter items, as in the continuous RAN format, predicts exception and non-word reading accuracy. As such, we aimed to elucidate the relationship between the RAN task and word identification processes that rely on phonological decoding and whole word recognition respectively. Bowers and Swanson (1991) demonstrated that continuous RAN formats contribute independent variance to word reading beyond that contributed by discrete formats, suggesting that the additional processes involved in continuous naming tasks are related to reading ability. In this experiment, we predicted that if visual and/or phonological processing of multiple items in RAN is particularly pertinent to word reading skill, then continuous task versions would contribute independent variance to exception and/or non-word naming accuracy.

Results from the regression analyses demonstrated that discrete, visual versions of RAN predicted exception- and non-word reading accuracy, but the continuous format did not contribute any additional variance. The converse effects were found for the phonological RAN, however. Whereas the discrete task version did not contribute independent variance to either exception or non-word decoding measures, the continuous task version contributed significant, unique variance to both measures.

When interpreting these results, it is firstly of note that when examining the amount of variance contributed by Letter sets to exception and non-word reading, a similar amount of variance is contributed to both measures. This is perhaps not surprising, however, when the strength of the correlation between the two variables is considered. Although SV and PD are considered separate processes, they share a large number of processes, of which letter recognition is one important common denominator. As a result, studies show that the two processes are highly correlated, with small but significant independent variances (e.g., Bates, Castles, Luciano, Wright, Coltheart, & Martin, 2007). Although speculative, stronger correlations between these processes may be a particular hallmark of skilled readers, for whom lexical processing is very well practiced, and made automatic to some extent. It is probable that the RAN measures in this experiment tap a more general word naming skill rather than unique characteristics of SV and PD skills.

Despite similarities in the dependent measures, the variance contributed by visual and phonological Letter sets varied as a function of the RAN format. Results from the visual Letter set conditions suggest that variance in word reading (both exception and non-word reading accuracy) could be accounted for by the discrete-static version of the RAN task, and that any additional variance contributed by the continuous-matrix format was not significant. In essence, these results suggest that taxing the visual system through activation of similar orthographic forms predicts word naming. However, *multiple* item presentation of letters taxing visual processes does not influence word naming. These results reiterate to some extent our results from the reaction time analysis. We suggest that the random presentation of letters may explain findings from both reaction time and regression analyses: The relative independence of RT and regression findings from task format suggest that rather than being driven by perceptual confusability, naming in RAN is influenced by recent memory activation of similar orthographic forms. The emphasis on orthographic processing in this task is strongly related to word reading accuracy, which buttresses Bowers et al's (1994) proposal that orthographic processing in RAN fosters its relationship with word reading.

In the phonological Letter sets, however, variance contributed by discrete-static conditions was not significant and *only* continuous-matrix conditions contributed unique variance to word reading accuracy (both exception and non-words). Multiple item processing that emphasises phonological aspects of RAN is therefore pertinent to word reading. In the phonological RAN, selecting the appropriate phonological label was taxed in that the decision involved choosing a label from a choice including a similar label. In the continuous-matrix condition, sequencing the multiple items was also necessary, which perhaps underlies its relationship with word reading. Sequencing items with an emphasis on phonology in the RAN may reflect the processes needed for word reading: selecting the appropriate phonological labels for individual graphemes whilst managing the additional information available for processing.

In summary, results from the regression analyses may elucidate and reconcile findings by Bowers and Swanson (1991) and Compton (2003). Bowers and Swanson demonstrated that continuous RAN formats contribute independent variance to reading ability when performance on discrete versions of the task is controlled.

Whilst this finding suggested that the additional processes involved in multiple item presentation are related to reading ability, it did not reveal whether visual or phonological processes are pertinent to this relationship. Compton was instrumental in demonstrating that phonological RAN Letter sets contributed independent variance to word reading, whereas visual Letter sets did not contribute unique variance. From these results, however, it is not possible to distinguish the influence of multiple item presentation over discrete presentation. In the present study, we demonstrated that the relationship between word reading and phonological Letters sets is contingent on multiple item presentation provided in the continuous-matrix format. Further, visual Letter sets do contribute variance to word reading, but this relationship is not dependent on the continuous format. Rather, *discrete* items that tax visual processes contribute unique variance to word reading.

The error rates in this study are fairly low for both groups (approximately 1%). However, a Kruskal-Wallis test demonstrated that the number of errors made by the dyslexic group were significantly larger than the mean number of errors in the non-dyslexic group. These findings concord with the 2% errors for non-dyslexic readers and 4% for dyslexic readers found in previous studies (Vellutino et al., 1996; Stanovich, 1981). Moreover, a correlation analysis demonstrated a speed-accuracy trade-off between reaction times and error counts. In general, participants who were slower at RAN made fewer errors.

5.8 Chapter Summary

Our findings suggest that the ability to discriminate visual items influences the speed at which a series of lexicalised items can be retrieved; suggesting an influential role for visual processing in reading fluency. Further, dyslexic readers tend to be slower to name visually confusable items than non-dyslexic readers. Both visual and phonological information in RAN predict word reading accuracy, but this relationship is dependent on multi-letter processing for the phonological RAN.

CHAPTER 6

What comes next?

The role of parafoveal processes in fluency

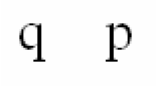
6.0 Chapter Overview

In Chapter 5, results from the RT data suggested that visual information influences the fluency with which lexicalised items can be named for non-dyslexic reading groups, and to a greater extent, dyslexic reading groups. We suggest that this effect was due to interference from activated representations of visually similar letter items. Experiment 3 investigates whether visual item confusion is exacerbated when the information is presented in parafoveal preview. Experiment 4 refines the letter stimuli and separates the influences of *visual* or *phonological* processes on RAN and reading fluency.

6.1 Juxtaposing confusable and non-confusable letters in the RAN

Experiment 2 demonstrated that activating visually similar orthographic representations yields longer latencies in RAN than activating similar phonological representations. These results imply an influential role for visual information in retrieving lexicalised items (as in both RAN and reading fluency). However, Experiment 2 did not include a baseline condition with which to compare the effects of visual and phonological confusability, and our conclusions are therefore limited. It is not clear, for example, whether our findings stem from genuine visual versus phonological processing differences, or are artefacts of our particular choice of letters. Furthermore, random presentation of letters in Experiment 2 allowed for increased variability within the confusability of items and in turn, participant responses. Confusable items separated by a large number of other items for example might lead to weaker confusability effects, compared with circumstances in which confusable items are juxtaposed in the RAN array. In order to address these issues, the experiments presented in this chapter involve controlled presentation of items in which adjacent letters are either paired for confusability or paired for non-confusability (which constitutes a baseline condition in which two adjacent letters are neither visually nor phonologically similar). Juxtaposing confusable letter pairs in the RAN presents an opportunity to investigate the effects of presenting a confusable letter following a similar item. By presenting adjacent, similar items in RAN, the participant must manage similar, potentially confusing information in parafoveal preview (the area flanking the right of the target) whilst naming the first item (see Figure 9). In order to overcome the potential for confusion, the participant requires efficient allocation of attention to parafoveal processes. (N.B. It should be noted here that when the participant is attempting to name the second letter in a confusable pair, activation from the first item may also interfere with naming. This issue is addressed empirically in the next chapter). In the following section, we will discuss parafoveal processing in normal reading and in relation to its potential deleterious effects on naming in dyslexia.

Figure 9: An example of a visually confusable letter pair.



Note: When processing the item *q*, the participant is required to manage potentially confusable information *p* available in parafoveal vision.

6.1.1 The role of parafoveal processing in reading

In alphabetic scripts, studies have shown that as well as processing information in the fovea (which spans about 2° of visual angle; Rayner, 1998), information is processed in the *parafovea*: the area flanking the fovea. In languages that read from left to right, processing in the parafovea extends to 4 letters to the left of fixation (Rayner, Well, & Pollatsek, 1980), whilst the region extends to 7-8 letter spaces to the right of fixation (Rayner, Well, Pollatsek, & Bertera, 1982; McConkie & Zola, 1987; Underwood & McConkie, 1985). In order to investigate the type of information extracted during parafoveal processing and how this information from the parafovea is integrated with the foveal stimulus, Rayner (1978) devised a contingent-change eye-tracking paradigm in which a word or letter stimulus is presented only in the parafovea. When the participant makes a fixation towards the stimulus, it changes into a target word, and the task is to name the word as quickly as possible. The effect of parafoveal information on target naming is assessed as a function of target naming time. This paradigm has been used to show that when the parafoveal prime is the same as the foveal word, naming is facilitated when the prime is presented 1°, 2.3° or 3° from fixation (to the right or left). Information from the parafovea therefore benefits subsequent processing time of that stimulus (Balota & Rayner, 1983; McClelland & O'Reagan, 1981; Rayner, 1978, Rayner, McConkie, & Ehrlich, 1978; Rayner, McConkie, & Zola, 1980), and is integrated across eye-movements (or 'saccades') with concomitant effects on subsequent foveal processing times.

Similarly designed studies both in eye-tracking and lexical-decision timed tasks suggest that orthographic information presented in the parafovea is integrated with subsequent foveal information (Inhoff, Starr, & Shindler, 2000; Kennedy, 1998, 2000; Rayner, 1975; Underwood, Binns, & Walker, 2000). Findings show that the preview benefit is not due to visual-feature detection, however. McConkie and Zola (1979) demonstrated that when the case of letters changed from fixation to fixation (e.g. MaNgRoVe to mAnGrOvE in one saccade) there was minimal disruption to the reading process. Preview benefit is therefore thought to derive from abstract letter codes rather than visual features of the word. Phonological information also integrates across saccades (Henderson, Dixon, Petersen, Twilley, & Ferreira, 1995; Pollatsek, Lesch, Morris, & Rayner, 1992), and there is evidence that a greater preview benefit is derived from phonological compared with orthographic information (e.g., Pollatsek, Lesch, Morris, & Rayner, 1992; Miellet & Sparrow, 2004). In general, information derived from the parafovea is low-level, however, and studies suggest that higher cognitive processing of morphological structures and semantic information is not integrated across saccades (Hyona, 1995; Rayner, Balota, & Underwood, 1986; Rayner & Morris, 1992).

As a result of being able to process information on an upcoming item in the parafovea, studies indicate that readers can make decisions on where to make subsequent fixations in the text. Short function words and words that are highly predictable from the text, for example, are more likely to be skipped altogether (e.g., Brysbaert & Bitu, 1998; Gautier, O'Reagan, & Le Garagasson, 2000), and saccade length is influenced by the length of the parafoveally presented word in addition to the currently fixated item (e.g., O'Reagan, 1979). Further, Sereno and Rayner (2000) demonstrated that judgements as to a word's orthographic regularity can occur in parafoveal preview. Orthographic regularity refers to the availability of a direct grapheme-to-phoneme mapping from the orthographic to the phonological representation of a word, and a number of lexical decision and naming studies demonstrate that participants are faster at reading low-frequency words (which are more likely to require phonological recoding) that also have transparent grapheme-to-phoneme correspondence (e.g., Baron & Strawson, 1976; Hino & Lupker 2000; Inhoff & Topolski, 1994). Sereno and Rayner showed that this *regularity effect* is only apparent in sentential reading contexts when parafoveal processing of the target is possible. These results suggest that readers use information from the parafovea to make decisions on where to make the next fixation and whether upcoming information warrants longer processing (fixation) time. Use of parafoveal processing can therefore maximise the fluency with which text is read.

The research reviewed thus far has focused on the influence of parafoveal information on *subsequent* fixations to that item. An additional body of work has suggested, however, that parafoveal information can influence currently fixated text. An immediate effect of parafoveal information on foveal processing has been demonstrated, suggesting foveal sensitivity to visual, orthographic, phonological, lexical and even some pragmatic information presented in the parafovea (Inhoff, Radach, Starr, & Greenberg, 2000; Kennedy, Pynt, & Ducrot, 2002; Murray, 1998; Pynte, Kennedy, & Ducrote, 2004; Underwood et al., 2000). So called 'parafoveal-on-foveal' findings are controversial, however. Such effects contradict the main premise of reading models such as the *E-Z reader* model (Morrison, 1984), which stipulate serial allocation of attention across text. According to serial models, parafoveal-on-foveal effects should not occur because covert attention is only allocated to the parafovea once processing of the foveal stimulus is complete. Further, parafoveal-on-foveal effects are not consistently replicated (e.g., Altarriba, Kambe, Pollatsek, & Rayner, 2001; Rayner et al., 1986; Rayner, Pollatsek, & Reichle, 2003; Rayner, White et al., 2003; Schroyens, Vitu, Brysbaert, & d'Ydenwalle, 1999). In this chapter, we do not distinguish between these reading models, but we return to this issue in Chapter 7.

6.1.2 Parafoveal processing in dyslexia

There is evidence to suggest that parafoveal processing varies as a function of reading ability, however. Chace, Rayner, and Well (2005), for example, conducted a similar design to Pollatsek et al. (1992), which included parafoveally presented homophone items (e.g., *beech* as a preview for *beach*) compared with an orthographic control (*bench* as a preview for *beach*). In contrast with skilled readers, there was no evidence that phonological codes contributed to the preview benefit for less skilled readers. Further, less skilled readers did not appear to benefit at all from information provided to the right of fixation, which fits with previous findings (e.g., Jared, Levy, & Rayner, 1999). Chace et al. suggest that since less skilled readers have more difficulty decoding fixated items, they cannot allocate sufficient attention to process parafoveal items.

Rather than viewing parafoveal anomalies as symptomatic of processing difficulty, another perspective is that they reflect deficits in visual attention. A deficit in visual attention, for example, could lead to ineffectual allocation of attention across orthographic items in the visual field (e.g., Whitney & Cornelissen, 2005). As a result, foveal processing of items might prove more difficult, but also gaining information from preview might be significantly impaired. One behavioural prediction stemming from this rationale that is consistent with a processing difficulty account is that dyslexic readers process *less* information in the parafovea than unimpaired readers. However, an approach emphasising the role of visual attention might argue that visual-attention deficits lead directly to parafoveal anomalies, rather than the parafoveal anomaly being secondary to a processing difficulty. Bosse, Tainturier, and Valdois (2006), for example, suggest that a visual attention deficit limits the number of visual elements that can be processed simultaneously. When processing words in an 'analytic' mode, these authors suggest that dyslexic readers' visual spans are not of an appropriate length to obtain optimal recognition of letters within words.

Evidence of impaired parafoveal processing in dyslexia also comes from lateral masking studies. Bouma and colleagues demonstrate that when isolated (e.g., ‘a’) or flanked (e.g., ‘xax’) letters are presented in parafoveal vision, normal readers show less accurate performance for flanked letters compared with isolated letters (Bouma & Ligein, 1977, 1980). For dyslexic readers, recognition levels of parafoveal items are generally similar to controls, unless information is presented in the fovea as well as in the parafovea. Parafoveal processing in reading is known to decrease as a function of foveal load (e.g., Henderson & Ferreira, 1990). Pernet et al. (2006), however, found that when a foveal item was presented, dyslexic recognition rates of isolated items in the parafovea were weaker than those of control readers. This finding supports previous results indicating that foveal letter presentation influences parafoveal processing (Salvemini, Stewart, & Purcell, 1992), and suggests that dyslexia involves a visual-attention deficit in more *complex* visual situations, requiring multi-item processing (e.g., Vidyasagar, 2004; Hawelka & Wimmer, 2005). These data suggest that a visual-attention deficit implicates confusion between (foveal and non-foveal) items in the visual field.

Moreover, studies consistently find that dyslexic readers show stronger decreases in recognition rates for flanked letters as a function of the number of letters presented compared with controls (Bouma & Ligein, 1977, 1980; Goolkasian & King, 1990; Klein, Berry, Briand, D’entremont, & Farmer, 1990). Findings by Pernet et al. (2006) suggest that lateral masking performance in dyslexia reflects increased difficulty relative to controls in integrating features of letters and their flankers in the parafovea. The involvement of magnocellular function in parafoveal processing (e.g., Omtzigt et al., 2002) may also imply a spatial-attention deficit contributing to difficulty in processing parafoveal items.

Rather than defining parafoveal processing as impaired in dyslexia, a number of researchers propose that visual attention deficits lead to *over* processing of parafoveal information. Geiger and colleagues, for example, demonstrated that whereas average readers show a sharp decrease in the accuracy with which parafoveal and peripheral letters are recognised as a function of eccentricity, dyslexic readers have a wider area of recognition in the right hemifield (e.g., Geiger & Lettvin, 1987; Geiger, Lettvin, Zegarra-Moran, 1992). Further, this bias is found to be an artefact of learning to read: whereas findings from English speakers yield a right-hemifield bias, dyslexic Hebrew speakers (reading from right to left) yield a left-hemisfield bias (Geiger et al., 1992). It is also possible to train dyslexic readers to narrow their attentional field (Geiger et al., 1994; Geiger & Lettvin, 2000).

Facoetti et al. (2000, 2003) propose that the perceptual strategy described by Geiger suggests a *diffused* mode of attention, whereby dyslexic children fail to learn how to mask irrelevant information from the periphery. Lorusso et al. (2004) show that this is characteristic of all dyslexic sub types, suggesting that a diffused attention mechanism impairs serial processing of words for decoding as well as lexical processing for exception word reading. In a recent model of word reading Whitney and Cornelissen (2005) provide a detailed explanation of how a diffuse or *parallel* reading strategy might impair word reading. If, for example, visual attention is dispersed over multiple letters, all letters will fire within the span of a single phoneme. As a result, establishing strong connections between individual graphemes and phonemes is more difficult, impairing grapheme-to-phoneme correspondence. Similarly, diffuse distribution of attention could impede letter-position encoding required for exception word reading (Cornelissen et al., 1998).

Experiment 3

The role of parafoveal processing in fluency

6.2 Rationale and predictions

From the review above, it is clear that parafoveal preview during reading enables the reader to process upcoming words in the text. As a result, readers can skip or spend less time on short words that are highly frequent, or words that are less frequent but with a regular orthography. For skilled readers, it is also therefore plausible that parafoveal preview of upcoming letter items in the RAN can facilitate naming times. In fact, the differences in parafoveal processing between groups of non-dyslexic and dyslexic readers may influence the disparity between naming times demonstrated by either group. Recall that in Experiment 1 (Chapter 4), non-dyslexic readers' latencies were facilitated by the presence of multiple items in the continuous-matrix format compared with discrete conditions, but this was not the case for dyslexic readers. Instead, they showed similar naming times regardless of the format in which the items were presented.

Experiment 3 therefore investigated the possibility that parafoveal information influences dyslexic and non-dyslexic readers' naming time differences. To achieve this, adjacent pairs of confusable (similar) items were presented within RAN trials and were compared with trials in which the same letters appeared adjacent to letters with which they were non-confusable. To test whether the effects obtained in this experiment were due to parafoveal effects (as opposed to recent activation of items) we compared confusable and non-confusable trials across the continuous-matrix and discrete-static conditions used in Experiments 1 and 2. (N.B. The discrete-matrix format was not included because previous results suggest that it contributes little to RAN performance beyond the discrete-static condition. Henceforth, the conditions included in this experiment will be referred to simply as *continuous* and *discrete* formats). Moreover, the role of visual and phonological information in parafoveal processing across reading groups was assessed by using Letter sets containing only visually confusable information (e.g., *p* and *q*) versus visually *and* phonologically confusable information (e.g., *b* and *d*).

Although there was some overlap in the letters used in each Letter set, items were mostly different across sets. It is important to note here that visual and visual-and-phonological Letter sets were not entered as a factor into the same analysis, therefore, as any differences might be interpreted in terms of the specific letters used rather than visual and phonological differences. Experiment 3 yielded two separate 2 (dyslexic vs. control) x 2 (discrete vs. continuous) x 2 (confusable vs. non-confusable) design for the visual and visual-and-phonological Letter sets.

If similar visual and/or visual-and-phonological information influences RAN performance, we predicted that in general, trials that included confusable pairs would yield longer latencies compared with trials that included non-confusable pairs. Further, if dyslexic readers are *more* susceptible than non-dyslexic readers to the effects of adjacent, confusable items, we expected a Group x Confusability interaction, such that confusable items would increase dyslexic readers' latencies to a greater extent than non-dyslexic readers' latencies. We also expected a Group x Format interaction in this experiment, demonstrating a similar pattern of results to previous experiments: non-dyslexic readers were expected to show a facilitation effect for continuous formats, whereas dyslexic readers were not. A Confusability x Format interaction was expected, such that the confusability effect would only be found in continuous and not discrete formats if confusable items had an effect on parafoveal processing rather than activation of memory representations. Critically, a 3-way Group x Format x Confusability interaction was expected, such that dyslexic readers would show higher or lower latencies relative to non-dyslexic readers in response to confusable items in the continuous format. Specifically, if dyslexic readers process too much information in the parafovea, we expected that they would show slower latencies relative to non-dyslexic readers under these conditions. If, on the other hand, dyslexic readers process less information in the parafovea compared with controls, we expected that dyslexic readers would demonstrate *faster* latencies in these conditions: processing less information in the parafovea might be beneficial to naming times when parafoveal information poses potential confusion.

Finally, if the predicted effects of adjacency and specific parafoveal processing described above were the result of visual processes, we expected similar results in both the visual and visual-and-phonological Letter sets (i.e., the addition of phonological similarity in the latter set would not influence the results). If, on the other hand, phonological processing is critical in influencing adjacency and parafoveal effects, we expected significant results of the effects described above only in the visual-and-phonological Letter set analysis. If our findings demonstrate an influence of visual processing on RAN, the results will support Wolf and Bowers' (1999) hypothesis of *extra*-phonological influences on RAN. If we find effects only in the Letter set including a phonological component, our results will support the hypothesis that RAN is a measure of phonological skill (e.g., Clarke et al., 2005; Wagner et al., 1993).

6.3 Method

6.3.1 Participants

Participants comprised 20 young British native English speaking adults with dyslexia (11 females and 9 males) and 20 with average to good reading skills (10 females and 10 males). Participants were recruited from the student population of the University of Edinburgh, and the mean age was 22 years and 1 month (*SD* = 4.65) for the dyslexic group and 22 years and 10 months (*SD* = 4.54) for the non-dyslexic reading group, yielding no significant age difference between groups (*t* = .03, *n.s.*). Participants from the dyslexic group were formally diagnosed with dyslexia and verbally reported that they knew of no other linguistic or behavioural disorder that might confound their performance. Students were recruited using advertisements and were paid for their participation.

6.3.2 Materials and Design

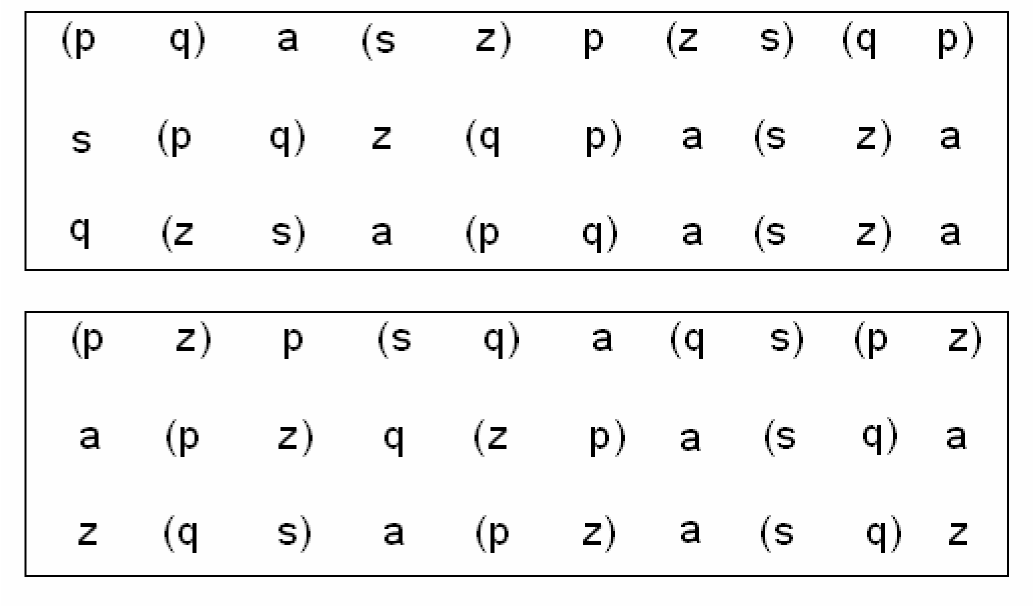
6.3.2.1 Cognitive and literacy tests

As in with previous experiments in this thesis, a cognitive profile for each participant was obtained, comprising a spelling and word recognition test (Wide Range Achievement Test [WRAT-3]; Wilkinson, 1993), non-word and exception word reading (Lum et al., 2001; Manis et al., 1996: see Appendix A and B) assessing phonological decoding and whole word recognition respectively) and a digits forwards and backwards measure of short term and working memory was used (Miles, 1993). We also implemented a measure of non-verbal IQ (Raven's APM).

6.3.2.2 Experiment

Letters were presented in Arial 18 point font at 1° viewing distance in black type on a white background. The experiment comprised a 2 (dyslexic vs. average readers) x 2 (discrete vs. continuous formats) x 2 (confusable vs. non-confusable letter pairs) design. As with previous experiments, the *continuous* condition involved simultaneous presentation of letters in a 10 x 3 matrix (per trial). In the *discrete* condition, individual letters were presented serially in a single centred position. Within each Letter set, letters were paired for confusability (visual / visual *and* phonological similarity) or non-confusability (being visually / phonologically different). Confusable visual pair combinations included the letters p–q; s–z; y–v and l–f. Non-confusable visual pairs included the combinations p-z; q–s; y–f and l–v. Confusable visual *and* phonological pair combinations included the letters b–d; m–n; d-p and c-e. With the exception of the pair m–n (that was based on onset confusability), phonological confusability was based on similarity of rimes. Non-confusable pairs included b-n; m-d; d-e; c-p. Confusable items were selected in this experiment by asking three independent raters to choose items from the alphabet considered to be visually or visually-and-phonologically confusable. Letter pairs chosen by two or more raters were included in the experiment. Each trial consisted of two confusable / non-confusable pairs repeated 10 times in counterbalanced order (e.g., p-q followed by q-p). Each confusable letter was also presented once in each trial as a filler item, and a constant filler 'a' was used 6 times in each trial (see Figure 10 for an example of a confusable and non-confusable trial in the Visual Letter set).

Figure 10: A schematic of one trial each in the confusable (top) and non-confusable (bottom) trials in the Visual Letter set. (Brackets were not included in the experiment itself, but illustrate which items are paired for confusability).



(p q) a (s z) p (z s) (q p)
s (p q) z (q p) a (s z) a
q (z s) a (p q) a (s z) a

(p z) p (s q) a (q s) (p z)
a (p z) q (z p) a (s q) a
z (q s) a (p z) a (s q) z

6.3.3 Procedure

6.3.3.1 Cognitive and literacy tests

As in Experiment 2, the background tests took approximately 40 minutes to administer. The main experiment was run in E-prime on a PC, and participants were again seated at a 60cm distance from a 15” RM monitor. As with previous experiments, the discrete condition was connected to a voice-activated relay (see Chapters 4 and 5) and the final letter required a manual response. In the continuous matrix, letters were presented with a 2° distance between each item and a manual response was required following the last item in the trial.

6.3.3.2 Experiment

Participants were given a two-trial practice in each condition before the experimental session commenced. A Latin square design was used to counterbalance the format condition. Participants alternated on whether they began with the Visual or Visual-and-Phonological block of trials. Each condition (e.g., visual – confusable in the discrete condition) comprised 4 trials, each comprising 30 randomised presentations of 5 letters, yielding a total of 32 trials. The experimental session lasted approximately 30 minutes in total.

6.4 Results

6.4.1 Cognitive and literacy tests

As in previous experiments, dyslexic readers obtained reliably lower standardised scores than non-dyslexics on spelling and word reading sections of the WRAT-3 (Table 10). The dyslexic group also scored below the normal range of scores for this age group. The dyslexic group also obtained lower scores on non-word and exception word naming (error count) and backwards digit span. In this sample of the dyslexic population, two participants scored within 1.5 SD of the non-dyslexic mean across variants of the RAN. Both participants obtained non-word reading errors 1.5 SD above the non-dyslexic mean, however, and scored within 1SD of the non-dyslexic mean on IQ. We did not therefore omit their data from the analysis.

Table 10: Reading group standardised scores on measures of spelling and word reading

		Dyslexic	Non-dyslexic	*t*	Cohen's *d*
Spelling	Mean	94.90	116.60	5.71**	1.81
	SD	15.83	6.17		
Word reading	Mean	96.2	115.85	4.78**	1.51
	SD	16.44	8.18		
Non-words	Mean	11.45	1.95	6.26**	1.98
	SD	6.36	2.35		
Exception words	Mean	4.10	1.10	3.39*	1.07
	SD	3.77	1.21		
Forward digit span	Mean	9.22	9.83	.83	0.27
	SD	2.23	2.29		
Backwards digit span	Mean	3.22	4.95	3.71**	1.22
	SD	1.62	1.17		
Raven's APM	Mean	10.60	10.88	.42	0.14
	SD	2.43	1.31		

Note. **p* < .01; ** *p* < .001; Spelling and Word reading = standardised scores. Non-word naming = errors /44. Exception word naming = errors / 45. Forwards digit span = /12; Backwards digit span = /6 points. IQ = /12.

6.4.2 Reaction times

Mean participant RT (ms) to complete all trials in each condition were calculated (see Table 11 and Figures 11 and 12). A sum of reaction times across each trial was obtained for both discrete and continuous formats. RTs falling above or below 3 SDs relative to the Group mean were excluded from the analysis. Two separate three-way mixed-design ANOVAs were conducted for Visual (VIS) and Visual-and-Phonological (VIS+PHON) letter sets. Each analysis contained the factors Group (dyslexic, non-dyslexic), Format (continuous-matrix, discrete-static) and Confusability (confusable, non-confusable).

Table 11: Group means and standard deviation latencies (ms) across Format and Confusability conditions in Visual and Visual and Phonological Letter sets.

		Non-dyslexic		Dyslexic	
		Conf	Nonconf	Conf	Nonconf
Visual	Discrete	13745 (1441)	13388 (1451)	15593 (2796)	15223 (2743)
Visual	Continuous	12643 (2386)	12420 (2413)	18466 (3733)	17373 (3725)
Visual + Phonological	Discrete	13562 (1794)	13258 (1435)	15261 (3251)	14858 (2539)
Visual + Phonological	Continuous	12185 (2461)	12255 (2800)	17220 (3807)	12255 (3464)

Figure 11: Group mean RTs and standard deviations in Confusable and Non-confusable conditions across Format conditions in the Visual Letter set.

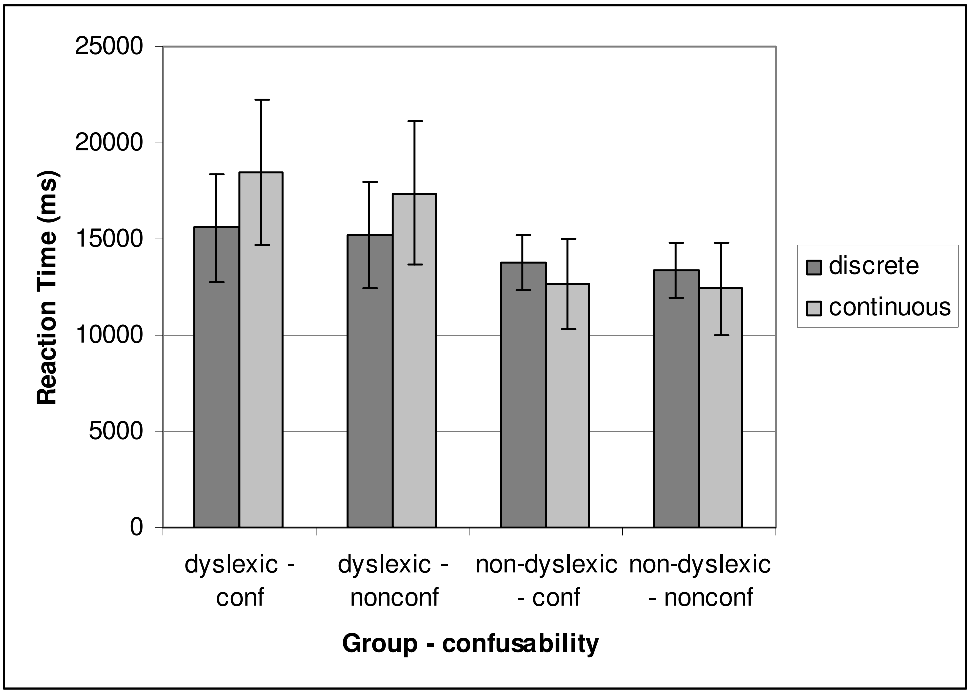
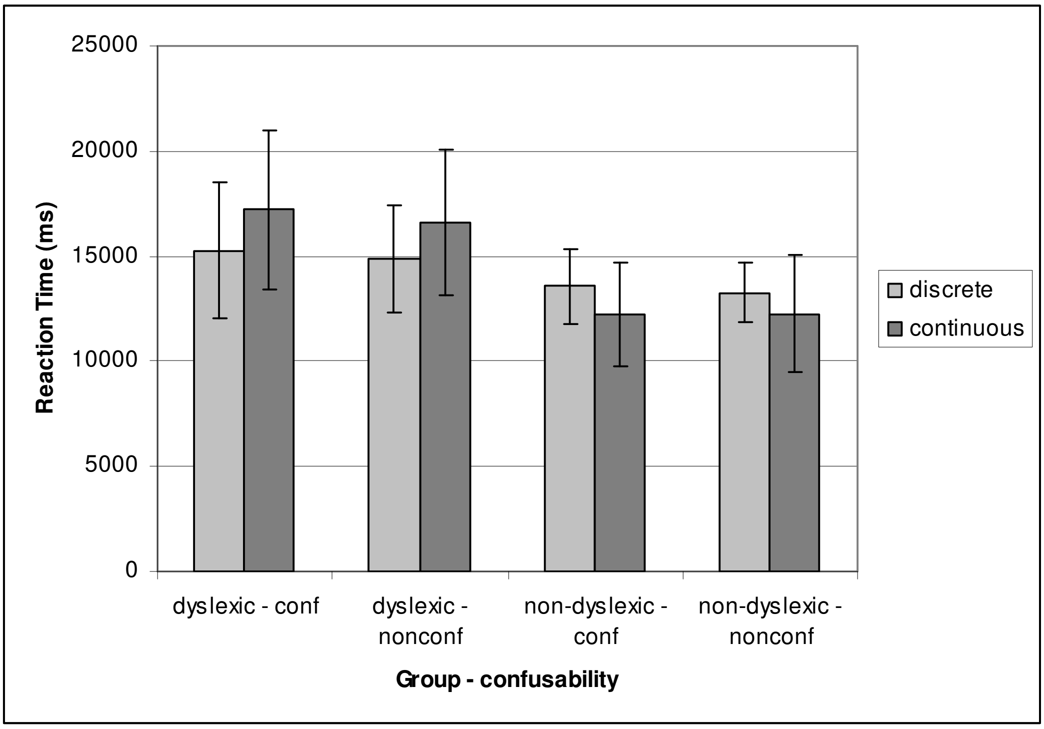


Figure 12: Group mean RTs and standard deviations in Confusable and Non-confusable condition across Format conditions in the Visual and Phonological Letter set.



Both analyses yielded significant findings across the same factors: In general, the dyslexic group yielded longer latencies than controls (VIS: *F* (1, 38) = 26.8, $p < .001$, $\eta^2 = .41$; VIS+PHON: *F* (1, 38) = 21.08, $p < .001$, $\eta^2 = .36$). Confusable items also elicited longer latencies in general compared with non-confusable items (VIS: *F* (1, 38) = 11.39, $p < .001$, $\eta^2 = .23$; VIS+PHON: *F* (1, 38) = 5.22, $p < .05$, $\eta^2 = .12$), but Group did not vary as a function of confusable versus non-confusable items (VIS: *F* (1, 38) = 2.12, *n.s.*; VIS+PHON: *F* (1, 38) = 1.97, *n.s.*). Further, there was no main effect of Format in either analysis (VIS: *F* (1, 38) = .11, *n.s.*; VIS+PHON: *F* (1, 38) = .51, *n.s.*), but a Group x Format interaction emerged in both analyses (VIS: *F* (1, 38) = 15.24, $p < .001$, $\eta^2 = .29$; VIS+PHON: *F* (1, 38) = 8.77, $p < .01$, $\eta^2 = .19$). A post-hoc analysis investigating the variable Format within each group revealed that the non-dyslexic group were slower on discrete compared with continuous formats (VIS: *F* (1, 19) = 4.73, $p < .05$, $\eta^2 = .19$; VIS+PHON: *F* (1, 19) = 6.29, $p < .05$, $\eta^2 = .24$). Conversely, the dyslexic group were slower on the continuous compared with the discrete condition (VIS (marginal effect: F (1, 19) = 4.15, p = .05, η^2 = .17; F (1, 19) = 10.53, p < .01, η^2 = .35). We found no evidence of a 3-way Group x Format x Confusability interaction, however (VIS: F (1, 38) = 2.41, *n.s.*; VIS+PHON: F (1, 38) = .95, *n.s.*).

6.4.3 Errors

An error analysis was next conducted across trials (see Tables 12 and 13). Overall, the dyslexic group made 2% errors, whereas the non-dyslexic group made 1% errors. Although the dyslexic group tended to produce more errors across conditions, a significant group difference only emerged in the VIS+PHON Letter set in the confusable-continuous condition. The marginal group differences in error rate contrasts with the strong group differences in RT.

Table 12: Group error counts (averages and SDs) across the factors *confusability* (confusable, non-confusable) and *format* (discrete, continuous) in the Visual Letter set.

	VIS – disc.		VIS – con.	
	Conf.	Non conf.	Conf.	Non conf.
Non-Dyslexic	0.60 (0.88)	0.45 (0.60)	0.45 (0.75)	0.25 (0.55)
Dyslexic	0.90 (0.91)	0.85 (1.46)	0.75 (0.85)	0.50 (0.88)
X²	1.5	.09	.05	3.3

Table 13: Group error counts (averages and SDs) across the factors *confusability* (confusable, non-confusable) and *format* (discrete, continuous) in the Visual and Phonological Letter set.

	VIS+PHON – disc.		VIS+PHON – con.	
	Conf.	Non conf.	Conf.	Non conf.
Non-Dyslexic	0.70 (1.21)	0.45 (0.82)	0.35 (0.67)	0.20 (0.53)
Dyslexic	0.60 (0.74)	0.90 (0.97)	0.90 (0.96)	0.70 (1.21)
X²	1.8	.7	4.1*	2.9

Note: * p < .05

Next, a Wilcoxon test investigated the difference between confusable and non-confusable conditions in each Letter set. No significant differences were found, however (Visual-discrete: $Z = 0.67$, *n.s.*; Visual-continuous: $Z = 0.14$, *n.s.*; Phonological-discrete: $Z = 1.44$, *n.s.*; Phonological-continuous: $Z = 1.02$, p = n.s).

6.5 Discussion

In this experiment, we taxed visual and phonological domains (by juxtaposing confusable items) in order to investigate the potential effects on naming fluency. In so doing, we hoped to further elucidate the low-level processes underlying reading fluency. Previous studies demonstrate that parafoveal preview is an important component of reading fluency in that it influences the length of time readers spend processing words within sentences (e.g., Balota & Rayner, 1983; McClelland & O'Reagan, 1981; Rayner, 1978, Rayner, McConkie, & Ehrlich, 1978; Rayner, McConkie, & Zola, 1980). Dyslexic and non-dyslexic reading groups' naming times were therefore compared on confusable letter pairs presented either in continuous or discrete RAN formats. We predicted that if juxtaposing confusable items influences naming speeds, confusable trials would yield longer latencies than non-confusable trials. Further, if confusable trials had more of an impact on dyslexic readers, we expected a Group-by-Confusability interaction. We also expected that if juxtaposing confusable items was a parafoveal effect, we would find longer latencies in the continuous format relative to discrete conditions, and if this effect was disproportionately larger for the dyslexic group, we expected a Group x Confusability x Format interaction.

The results of this experiment showed that consistent with all of our previous findings, the dyslexic group were generally slower at RAN than non-dyslexic readers. With reference to our manipulations, we found that whereas confusable information influenced naming latencies in general, the effect was not heightened in the dyslexic group relative to the non-dyslexic group. These findings suggest that although a confusability effect occurred, it did not affect dyslexic readers more than non-dyslexic readers. Further, the effect of presenting pairs of confusable items in the continuous format did not yield higher latencies compared with discrete formats, and these variables did not interact with the Group. We found no evidence, therefore, to suggest that confusability elicited through juxtaposing visually confusable items is a specific parafoveal effect. The confusability effect did not involve distinguishing visual information in the parafovea from a foveal item (e.g., Kennedy, et al., 2002) or integrating visually confusable information whilst fixating an orthographically similar item (e.g., Rayner et al., 1982). Since the confusability effect was just as likely to occur in the discrete condition, we must conclude that the effect comprised activation of similar visual or orthographic features dependent on memory traces rather than parafoveal processing. Our conclusions are therefore similar to the results of Experiment 2, suggesting that activation of visually similar features influenced naming times, but the effect does not depend on the visual availability of both confusable items. The absence of a 3-way interaction in this experiment also suggests that the confusability effect for both reading groups depends on activation of similar memory representations rather than visual perception of items.

In accordance with findings from previous experiments in this thesis, non-dyslexic readers in this experiment showed facilitation for multiple visual items. A new finding, however, was that dyslexic readers demonstrated the opposite pattern of results to non-dyslexics: as depicted in Figures 11 and 12, dyslexics yielded higher latencies on the continuous format relative to the discrete format. This finding therefore builds on previous experiments. In Experiments 1 and 2, the letters used were relatively non-confusable: even in the visual-and-phonological sets of Experiment 2, similar items only comprised two letters within each set of five letters. In the present experiment, however, *four* of the five letters were either visually or visually and phonologically confusable, allowing more scope for confusion between items.

It would appear that the heightened confusability in this experiment brought to light a difficulty for dyslexic readers in processing the multiple visual items presented in the continuous format compared with processing individual items in the discrete format. Although there is no evidence in the current experiment to suggest that this effect reflects parafoveal processing strategies, this finding indicates that processing multiple visual items is difficult for dyslexic readers (e.g., Hawelka & Wimmer, 2005). In support of this interpretation, Pernet et al. (2006) demonstrated that in general, lateral masking is not sensitive to perceptual features of letters, and instead depends on later perceptual stages: feature detection of letters occurs accurately, but features of targets and flankers are more likely to be integrated with each other, leading to confusion and higher probability of errors (Levi, Hariharan, & Klein, 2002; Pelli, Palomares, & Majaj, 2004). For dyslexic readers, isolated parafoveal items may be accurately processed in terms of visual features, but interference could occur between foveal and parafoveal orthographic representations. A visual attention deficit in dyslexia may serve to increase the crowding effect, such that information from the parafovea effectively serves as visual *noise*, which interferes with rapid access to representations associated with the foveated letter.

This explanation of the Group x Format interaction is necessarily tentative, particularly in view of the extrapolation of findings from lateral masking studies (in which items are integrated in the parafovea) to RAN (in which we suggest that items are integrated between the fovea and parafovea). It may, however, explain why dyslexic readers are slower to name multiple visual items, apparently irrespective of the type of information that is presented. An alternative explanation of the current results, however, is that our dependent measure (summing reaction times across all items within the trial) is not sufficiently sensitive to yield group differences, and this issue is addressed in Chapter 7.

A final point is that these results were found across both Letter sets, suggesting that the findings in this experiment are robust with respect to visually confusable items. Of note is the finding that including phonological information in the second set did not influence the results. It is possible, however, that similar rime information is not prone to confusability, and in the following experiment we investigate other means of invoking phonological confusability. We also impose tighter control over definitions of *confusability*.

Experiment 4

The effect of juxtaposing visual, onset or rime information

6.6 Rationale and predictions

Experiment 4 pursued the issue of visual versus phonological effects on naming fluency using tighter control over the variables compared with the control exerted in Experiment 3. Visual and phonological confusability were kept distinct as far as possible between letter sets, and an additional letter set was included to investigate the effects of confusable phonological *onsets* on RAN latencies. The rationale for these modifications is set out below. In Experiment 4 we therefore contrast the effect on RAN latencies of presenting pairs of visually confusing letters (e.g., *t* and *j*) with two types of phonologically confusable letters: those whose names have confusable onsets (e.g., *g* and *j*) and those with confusable rimes (e.g., *b* and *v*).

Results obtained from Experiment 3 suggested that juxtaposing visually confusable items resulted in slower naming times for both reading groups, but this effect could not be attributed to a parafoveal effect (the confusability effect was similar across continuous and discrete formats) and dyslexic readers were not more prone to interference from confusable items compared with controls (confusability did not interact with reading group). Moreover, these findings were consistent across visually confusable and visually *and* phonologically confusable letter sets, suggesting that the addition of phonologically confusable information did not influence RAN latencies.

The inclusion of *visual* and *visual-and-phonological* conditions in Experiment 3 was useful for examining whether visual or phonological processes exert an influence on RAN. Wolf and Bowers (1999), however, emphasise the multi componential role of naming and fluency, in which visual *and* phonological domains are probably implicated. As such, in Experiment 4 we decided to include Letter sets that separated the visual and phonological confusability as much as possible so that we could clearly judge whether effects are found in either domain, or both.

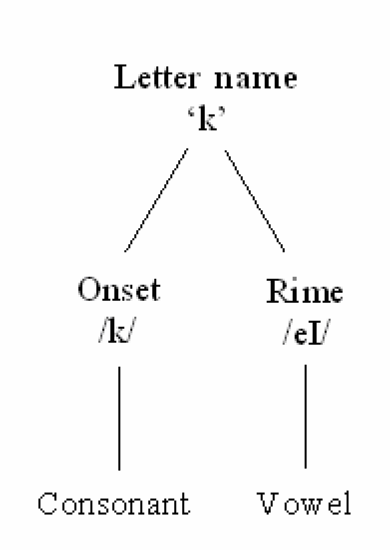
Further, the validity of visual versus phonological findings in Experiment 3 depends on sufficient control over extraneous variables which may have biased the results, particularly with respect to the influence of visual and phonological factors on RAN naming times. In claiming a distinction between a *visual* and *visual-and-phonological* Letter set, for example, it is necessary that the latter Letter set includes phonological features that are more prone to confusion compared with items in the former letter set. In Experiment 3, however, the ‘visual’ condition included pairs of items that were not controlled for consonant-vowel (C-V) pronunciation of the letter name. The letter names for the pair *s* and *z*, for example, contains V-C /es/ and C-V /Zed/ pronunciation, as well as sharing the vowel /e/ and similar sonorant consonants /s/ and /z/. These phonological features of the *visual* condition may have proved every bit as confusable as the similar rime information introduced in the *visual and phonological* condition. In Experiment 4, we therefore decided to control for these potential confounds by only including letters with names that require C-V pronunciation. Further, unless it was part of the manipulation, we only included letters within each set with names containing minimal phonological overlap.

It is also possible that the addition of phonological confusability in Experiment 3 exerted no demonstrable effects on RAN speed because rime information is not a source of confusion for reading fluency. A by-product of the *similar* rime information used was that letters rhymed with each other (e.g., /bee/ and /dee/). Developmental studies demonstrate that knowledge of rhyme relationships between word rimes in English is critical in learning to read (Goswami, 1999; Goswami & Bryant, 1990). Goswami (1988) demonstrated that knowledge of the word *beak*, for example, facilitated their ability to read words with similar rimes, such as *peak*, illustrating that children learn to recognise words by drawing on larger units of stored words than just alphabetic, or phonemic properties. Dyslexic children’s difficulty in learning to read has therefore been attributed to a failure to make analogies between words (Goswami, 1994). Hanley, Reynolds, and Thornton (1997), for example, showed that participants with dyslexia read fewer analogous words to a clue word (with a similar rime) compared with controls. Further, dyslexics' use of rime analogies for word recognition correlated with their performance on a rhyme detection test.

Children's natural tendency to use rime analogy when reading may have been overestimated, however (Bowey, 1996, 1999; Muter, Snowling, & Taylor, 1994; Savage, 1997), and Brown and Deaver (1999) showed that children prefer to use grapheme-to-phoneme correspondence compared with analogies to stored rimes when decoding non-words. Further, in a longitudinal study, Muter, Snowling, and Taylor (1994) found no evidence to suggest that rhyming ability at 4 years of age predicts the use of end-of-word analogies at age 6. At 6 years, however, children's rhyming skill was related to lexical analogies, suggesting that rime information may be a more important feature of reading later in development.

The rime of letter names (like the rime of words) also comprises the largest phonological component of the output, suggesting that rapid access to the appropriate rime may be critical for good performance on the RAN task. Moreover, as discussed in Chapter 5, maintaining items with similar rimes in WM is more difficult than for items with dissimilar rimes (Conrad, 1964; Hulme, 1984) and some evidence suggests that the effect is augmented for dyslexic readers (Johnston, Rugg, & Scott, 1987). However, studies examining which component literacy skills facilitate reading ability suggest that letter-sound knowledge, or grapheme-to-phoneme correspondence is more pertinent than rime awareness (Bowey & Underwood, 1996; Coltheart & Leahy, 1992; Laxon, Masterson, & Coltheart, 1991; Seymour, Duncan, & Bolik, 1999). It would appear that in contrast with grapheme-to-phoneme rules, rime awareness develops as a later feature of reading, when lexical-orthographic knowledge is more firmly established. Owing to these findings, Experiment 4 included two phonological conditions, in which confusable *rime* and *phonemic* information were separated. The rime condition comprised letters with confusable (similar) rimes (e.g., *b* and *v*) in the letter name, whilst the onset condition included items with confusable initial phonemes (e.g., *g* and *j*) in the letter name. Our use of both types of confusable phonological information allowed us to maximise the chances of detecting a potential phonological effect, as well as attributing the effect to either the phonological (onset) property of the item or the rime (see Figure 13 for a schematic of how the phonological properties of a letter name can be distinguished).

Figure 13: Structure of the letter name *k*.



In sum, Experiment 4 was an attempt to refine the letter items used in order to evoke visual and phonological confusability, using stricter experimental control. First, all items in the experiment had C-V pronunciation in order to control for spurious phonological variability between letter sets. Second, rime, onset and visual confusability were manipulated in separate letter sets, and objective measures of confusability were used in order to select appropriate letters. Onset and rime letter sets comprised letters with confusable (identical) onsets and rimes, respectively. Conversely, visual items comprised visually similar letters, but also with minimal phonological confusability. Specifically, letters were chosen that had a 25% probability of being confused when the visual system is taxed, such as when letters are being viewed from long distances or with high eccentricity (Bouma, 1971). Finally, an additional aim of this experiment was to select appropriate letters to test for confusability in the RAN, which would then be replicated in an eye-tracking experiment. As discussed in Chapter 5, null effects of confusability when compared across discrete and continuous formats might reflect the insensitivity of these measures rather than a genuine null effect. Summing and comparing discrete RTs with a total time measure is prone to considerable error, which may mask potential parafoveal effects. We investigate the role of specifically parafoveal processes further in the Chapter 7 using different methodology, but for the current purposes, letters are presented only in the continuous format.

In this experiment, we predicted that if, under strict experimental control, visual confusability between items influences naming time, confusable pairs would yield longer latencies overall than non-confusable pairs. Such a finding would corroborate results from Experiment 3. A similar effect was expected if items paired for onset or rime confusability influenced naming speeds. The presence or absence of a confusability effect in each letter set would indicate the relative importance of visual and phonological processes. If, for example, an effect was only found in visual *or* phonological sets, this was taken to suggest that the information provided in that letter set (i.e. visual or phonological information) had primacy in its influence over RAN latencies, and comprised an influential low-level factor in reading fluency. If taxing both types of information influenced the results, however, there would be evidence to suggest that both types of information influence RAN latencies and reading fluency. We also predicted that the letter set that yielded disproportionately longer latencies for the dyslexic group (on confusable items) relative to the non-dyslexic group would reflect the type of information processing difficulty experienced by the dyslexic readers.

6.7 Method

6.7.1 Participants

Two groups of 20 (13 females; 7 males) native-English speaking dyslexic and non-dyslexic (mean ages 21.55 (*SD* = 2.31); 21.3 (*SD* = 3.48), yielding no significant difference (*t* = .23, *n.s.*)) were paid for participation. Dyslexic participants were formally assessed and reported no other known linguistic or behavioral disorder.

6.7.2 Materials and Design

6.7.2.1 Cognitive and literacy tests

The cognitive and literacy tests used in this experiment were identical to those used in Experiment 3 (See section 6.3.2.1 and Appendix A and B).

6.7.2.2 Experiment

Confusability (confusable, non-confusable) was manipulated in each Letter set (Onset, Rime, Visual) analysis. Each set comprised five letters. Onset items comprised letters sharing an onset (g – j (onset /dʒ/); k – q (onset /k/)). Rime items comprised letters sharing a rime (b – v (rime /i/); j – k (rime /eI/)). Visual items comprised letters with a 25% probability of being confused (Bouma, 1971) but minimal phonological confusability (g – q and t – j). In each set, the fifth letter was the filler z (pronounced /zεd/ in British English). Each letter appeared six times in a continuous-matrix format. Confusable items were presented adjacently or non-adjacently (Onset; j – q, g – k, Rime; b – j, v – k, Visual; t – g, j – q). The order of each letter pair was fully counterbalanced across trials.

6.7.3 Procedure

The procedure for administering the cognitive and literacy tests followed an identical procedure as that used in Experiments 2 and 3, and took a total of approximately 40 minutes to administer. In the experimental session, letters were again presented in Arial, point 18 font and an identical procedure to Experiment 1's continuous-matrix condition was used: a keyboard response was required to signify the end of the naming trial. Each letter set was used in four adjacent and four non-adjacent trials, yielding 24 trials in total. Trials differing in terms of Letter set and confusability were fully randomised to avoid practice effects with certain Letter sets and letter sequences. Each trial comprised 30 letters. The session lasted approximately 20 minutes.

6.8 Results

6.8.1 Cognitive and literacy tests

Dyslexic readers obtained lower scores than non-dyslexics on all assessment tests except non-verbal IQ, demonstrating lower levels of literacy than the non-dyslexic group (Table 14). Three participants in the dyslexic group obtained average RAN latencies within 1.5 SD of the non-dyslexic group's mean, but they all yielded error rates 1.5 SD above the non-dyslexic mean for non-word reading.

Table 14: Reading group scores on measures of spelling and word reading (standardised), non-word reading and exception word reading.

		Dyslexic	Non-dyslexic	*t*	Cohen's *d*
Spelling	Mean	100.9	116.0	5.3**	1.71
	SD	10.1	7.3		
Word Reading	Mean	102.9	115.4	3.4**	1.10
	SD	13.9	7.9		
Non-word reading	Mean	9.6	1.5	7.1**	2.29
	SD	4.8	1.4		
Exc.-word reading	Mean	3.4	0.7	3.9**	1.11
	SD	2.9	1.9		
Forward digit span	Mean	4.3	9.5	2.8**	2.93
	SD	1.2	2.2		
Backward digit span	Mean	3.5	8.7	2.9**	2.21
	SD	1.8	2.8		
Raven's APM	Mean	10.1	10.3	0.4	1.12
	SD	1.8	1.7		

Note. ** p < .001; Spelling and Word reading = standardised scores. Non-word naming = errors /44. Exception word naming = errors / 45. Forwards digit span = /12; Backwards digit span = /6 points. IQ = /12.

6.8.2 Reaction Times

We calculated mean participant RTs for the four trials per condition. Letter sets were entered into three separate two-way ANOVAs: Group (dyslexic vs. non-dyslexic) x Confusability (confusable vs. non-confusable). All three analyses yielded a main effect of Group: Dyslexics demonstrated longer latencies than non-dyslexics on all letter sets; Visual: F (1, 38) = 7.8, $p < .05$, $\eta^2 = .17$; Onset: F (1, 38) = 5.1, $p <$

.05, η^2 = .12; Rime: *F* (1, 38) = 5.6, $p < .05$, η^2 = .13. The Visual Letter set demonstrated a marginal Confusability effect (*F* = 3.58, *p* = .06), whilst the phonological letter sets (Onset and Rime) yielded a main effect of Confusability (Onset: *F* (1, 38) = 40.2, $p < .01$; Rime: *F* (1, 38) = 7.5, $p < .01$), with longer latencies in the confusable-adjacent condition.

Critically, only the Rime Letter-set analysis demonstrated a Group x Confusability interaction (*F* (1, 38) = 4.8, $p < .05$, η^2 = .11). Post-hoc tests showed that dyslexic readers obtained significantly longer RTs for confusable compared with non-confusable rime conditions (*F* (1, 19), = 11.20, $p < .01$, η^2 = .37). The non-dyslexic group did not show a significant difference in RTs across confusable and non-confusable conditions in the Rime Letter set, however (*F* = .18, *n.s.*). The non-dyslexic and dyslexic groups showed comparable performance on both onset and visual Confusability conditions (*F* = .46, *n.s.*; *F* = .31, *n.s.*). Table 15 and Figures 14, 15 and 16 demonstrate group differences across rime, onset and visual letter sets. Our results suggest that although dyslexics were generally impaired in processing phonologically- and visually-confusable letter sets compared to non-dyslexics, they demonstrated a particular impairment in processing adjacent letters with confusable rimes.

Table 15: Group means (ms) and standard deviations across rime, onset and visual letter sets in confusable and non-confusable conditions.

	Non-dyslexic		Dyslexic	
	Conf	Nonconf	Conf	Nonconf
Rime	14462 (2480)	14335 (2458)	17093 (3441)	16029 (3274)
Onset	17120 (2684)	15733 (2958)	19519 (3486)	17801 (3606)
Visual	15323 (1909)	15109 (2241)	17861 (3443)	17466 (3446)

Figure 14: Group means and standard deviations in the Rime letter set as a function of confusability.

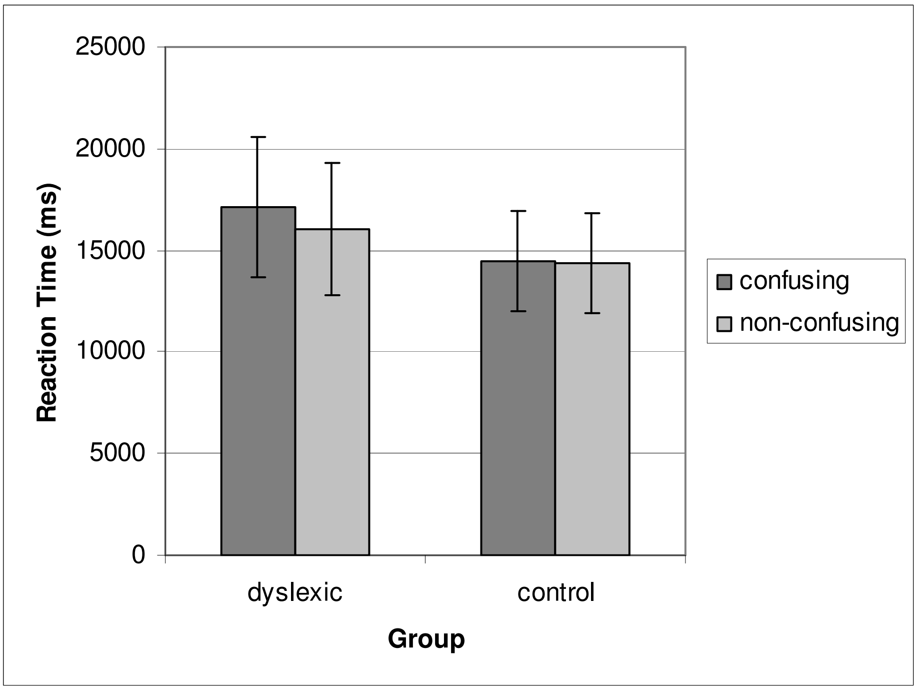


Figure 15: Group means and standard deviations in the Onset letter set as a function of confusability.

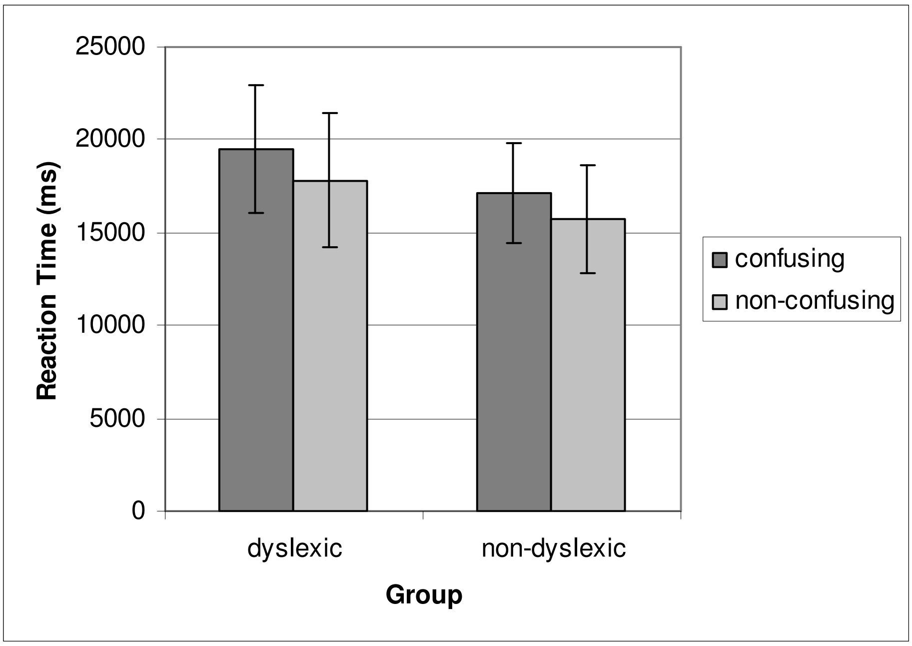
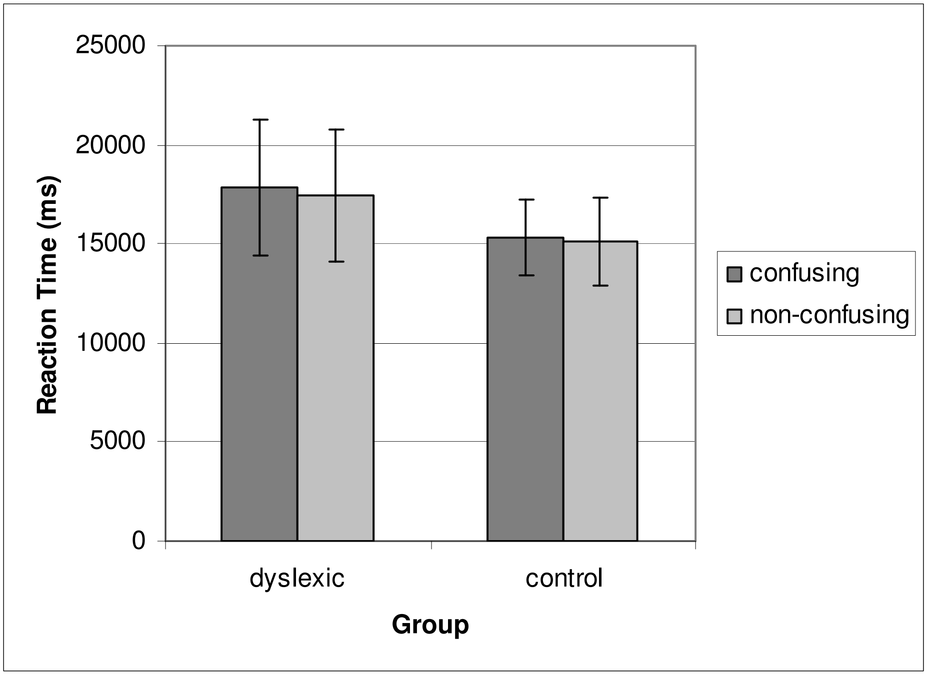


Figure 16: Group means and standard deviations in the Visual letter set as a function of confusability.



It should also be noted here that four of the participants in the dyslexic group participated in Experiment 3 of this thesis. Although there was a significant delay between the experiments (three months), it is possible that these participants were already familiar with the procedure, which may have influenced their performance on the task compared to the other members of the dyslexic group. We therefore conducted a separate analysis that excluded these members of the dyslexic group. Our analyses demonstrated almost identical results to the analyses comprising the full dataset: Dyslexics demonstrated longer latencies than non-dyslexics on all letter sets; Visual: F (1, 34) = 8.8, $p < .01$, $\eta^2 = .21$; Onset: F (1, 34) = 6.5, $p < .05$, $\eta^2 = .16$; Rime: F (1, 34) = 8.4, $p < .01$, $\eta^2 = .19$. The Visual Letter set demonstrated a marginal Confusability effect ($F = 3.8$, $p = .06$), whilst the phonological letter sets (Onset and Rime) yielded a main effect of Confusability (Onset: F (1, 34) = 37.2, $p < .001$, $\eta^2 = .52$; Rime: F (1, 34) = 7.2, $p < .01$, $\eta^2 = .17$), with longer latencies in the confusable-adjacent condition. Only the Rime Letter-set analysis demonstrated a Group x Confusability interaction (F (1, 34) = 4.6, $p < .05$, $\eta^2 = .12$).

6.8.3 Errors

Both dyslexic and non-dyslexic reading groups made approximately 2% errors in this experiment. As in Experiment 3, a Kruskal-Wallis comparison demonstrated a tendency for the dyslexic group to produce more errors in each condition relative to controls, but a significant group difference only emerged in the Visual non-confusable Letter set (see Table 16). Again, these findings contrast with robust group differences and confusability effects in the RT analyses.

Table 16: Group error counts (averages and standard deviations) across the factor Confusability in either Letter set.

	Visual		Onset		Rime	
	Conf.	Non conf.	Conf.	Non conf.	Conf.	Non conf.
Non-dys.	1.45 (1.66)	1.45 (1.35)	1.70 (2.27)	2.70 (1.41)	2.30 (2.67)	2.40 (3.06)
Dyslexic	1.80 (1.70)	2.80 (1.93)	1.70 (2.36)	3.15 (1.95)	2.25 (2.12)	3.05 (1.57)
X^2	1.7	8.8**	.02	.35	.08	3.7

Note: ** $p < .01$

A Wilcoxon test was used to examine the difference between confusable and non-confusable trials in each Letter set. A significant difference was only found in the Onset Letter set ($Z = 2.98$, $p < .01$). Neither Rime nor Visual Letter sets yielded effects of confusability in the error analysis, however (Rime: $Z = 1.36$, *n.s.*; Visual: $Z = 1.41$, *n.s.*).

6.9 Discussion

Experiment 4 investigated the potential contribution of visual and phonological factors to naming fluency. To accomplish this, we manipulated the confusability of Visual, Onset and Rime letter sets in the RAN by presenting similar letters adjacently (e.g., *g-j* in the onset condition) or non-adjacently (e.g., *g-k* in the onset condition). If the information provided in a specific Letter set influences RAN performance, we expected that the confusable condition in that Letter set would yield longer latencies overall. Furthermore, if a specific information type posed a particular problem for readers with dyslexia, we expected that the dyslexic group would show particularly increased naming times in the confusable condition for those Letter sets relative to the non-dyslexic group.

The results showed that non-dyslexic as well as dyslexic readers demonstrated longer RAN latencies when required to name two adjacent letters with similar visual properties. The ability to visually discriminate items in the RAN is therefore an influential component of latencies on the task, supporting our findings from Experiment 3. However, a number of participants in this experiment reported (following the experiment) that they did not find items in the Visual Letter set confusing. We investigate this issue further in Chapter 7. Confusable Onsets also impacted on naming times in Experiment 4, supporting the importance of letter-sound knowledge in reading ability (Bowey & Underwood, 1996; Coltheart & Leahy, 1992; Laxon, Masterson & Coltheart, 1991; Seymour, Duncan, & Bolik, 1999).

A critical Group x Confusability interaction emerged in the Rime letter set, however, such that the confusable (similar) rimes did not influence non-dyslexic naming times relative to non-confusable conditions, but confusable rimes resulted in longer latencies for the dyslexic group. Although this finding appears to support the importance of rime information in attainment levels of tasks pertaining to literacy (Goswami, 1999; Goswami & Bryant, 1990), other explanations may account for this result. First, the rime difficulty exhibited by the dyslexic group in this experiment might also reflect difficulty in selecting the appropriate onset to match an already activated rime. The inability to inhibit the onset e.g. /b/ for *b* and access /v/ to articulate *v* may reflect impaired degraded phonemic representations, for example (e.g. Snowling, 2000). Second, although the Group x Confusability interaction was significant, replication of this effect is required in order to make any firm conclusions regarding the role of rime information in dyslexia. In particular, a dependent measure involving summed RTs of 30 items, as in this experiment, is potentially prone to a large amount of error, which may have produced a *Type 1* error, in which an incorrect significant effect was found. This drawback, which is a criticism which can be levelled at the RAN in general and to the methodology used in the experiments reported thus far, is addressed in Chapter 7.

6.10 General discussion

The experiments reported in this chapter aimed to address the role of parafoveal processing in naming fluency, its relationship to different types of information processing (visual and phonological) and whether it discriminates groups of dyslexic and non-dyslexic readers. Results from Experiment 3 suggested that although visual confusability induced longer RAN latencies for both groups, there is currently no evidence that the findings stems from parafoveal effects and the effect was not heightened in the dyslexic group. Comparing summed RTs for continuous and discrete formats is subject to a large amount of error variance, however, and this technique may not provide an optimal measure of parafoveal effects. A different approach for investigating specific parafoveal influences within the continuous format is pursued in the Chapter 7. Experiment 4 in this chapter refined the letter sets representing different types of information processing involved in RAN using stricter item control. We also separated the influences of similar visual and rime items and included an additional phonological onset condition. The results indicated that on continuous formats, general RAN latencies are influenced by both visual and phonological onset information, but only the dyslexic group are influenced by rime information.

In sum, our results suggest that adjacent confusable visual and phonological information influence both reading groups, but thus far, there is no evidence to suggest that parafoveal factors influence visual and phonological processing in RAN. As discussed in the next chapter, pairing confusable letters also implicates executive processes, for example, which may influence fluency rates and be impaired in dyslexia. We cannot, therefore, make firm conclusions in this chapter concerning how low-level information processing in preview might influence reading fluency. This issue will be pursued in the next chapter, however, in conjunction with the extent to which naming pairs of confusable items is a function of simultaneous activation of the next item whilst naming the first item. Stemming from these questions are issues concerning which stages in processing or producing a lexicalised item are influenced by preview, or simultaneous processing of a target and neighbouring stimulus. The answers to these questions will help to elucidate the low-level processing characteristics of reading fluency. Further, our comparison of dyslexic and non-dyslexic readers will indicate which processes involved in fluency are vulnerable to impairment, resulting in disfluent reading rates.

6.11 Chapter Summary

This chapter investigated how visual and phonological processing combines with parafoveal processing to influence RAN latencies, as representative of the low-level processing requirements of fluent reading. Although confusable information in both visual (Experiment 3) and visual and onset (Experiment 4) Letter sets yielded longer latencies across both groups, there was no firm evidence that the effect was parafoveal in nature. Only confusable rime information impaired dyslexic readers relative to the non-dyslexic group (Experiment 4). In the next chapter, we use novel methodology to conduct a more fine grained investigation of individual-item processing *within* the continuous format. We will pursue the question of parafoveal effects in RAN as well as investigating the influence of executive processes.

CHAPTER 7

Sequencing a series of lexicalised items: Results from eyetracking

7.0 Chapter Overview

Experiments 3 and 4 suggested that confusable visual and phonological information presented adjacently in RAN increases naming latencies for both reading groups. In Experiment 5, we use eyetracking methodology to conduct a more fine-grained analysis of how parafoveal and multi-item processing in visual and phonological domains influence naming times. We also examine how processing time and the time taken from processing the stimulus to articulation vary as a function of confusability. Group comparisons also yield information concerning areas of dysfunction in the dyslexic group.

7.1 Eye tracking methodology as a means to study fluency

This thesis uses variations of the Rapid Automatised Naming task in order to elucidate the low-level processes underlying reading fluency. As noted elsewhere in this thesis, the traditional method employed in measuring RAN involves summing the reaction times of all 50 items within each trial. Whilst this measure has proven illuminating (e.g., Bowers 1988; Denckla and Rudel 1976a, b; Grigorenko, et al. 1997; Berninger 1995; Snyder and Downey 1995; Spring 1988; Wolf 1982; Wolf 1986; Wolff et al. 1990), it is prone to a great deal of error, since participants tend to repeat items or pause in order to check their place in the array. The sum of items within the trial is therefore a gross measure of RAN performance, and the error this engenders creates a sub-optimal environment for measuring the effects of specific items on participants' RAN latencies. In Experiments 3 and 4, for example, potential group differences in response to confusable items may have been masked. In this chapter, we employ eye-tracking methodology in order to overcome these potential sources of error. The principal advantage of eye-tracking methodology over off-line reaction time experiments is that we can measure the time taken to process each letter individually, but within the context of the continuous RAN format. Eye-tracking therefore presents a unique opportunity to decompose the continuous RAN in order to pinpoint which processes influence naming times as well as how reading groups differ on the task. Further, an on-line measure of eye movements yields a very precise indication of the temporal features of RAN processing: initial fixation on each item suggests *when* processing time begins on each letter.

7.1.1 Eye-tracking and production of object names

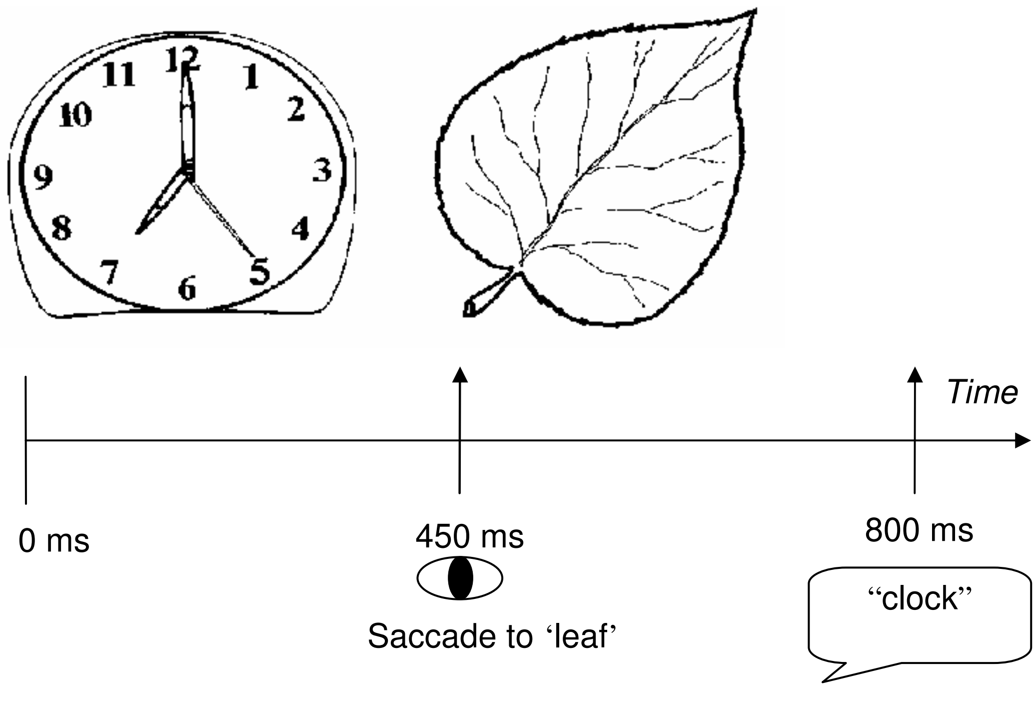
The premise for using eye-tracking for language research rests on the assumption that the location in which a person fixates her eyes reflects the general direction in which her attention resources are allocated (e.g., Rayner, 1975; although as reviewed in Chapter 6, attention can also be allocated to the parafovea and periphery of a visual stimulus). As such, eye tracking is widely used for studying low-level and linguistic processes on reading ability, as well as being used as a tool for studying higher psycholinguistic feats, such as comprehension and production of complex sentences and visual scenes (e.g., Griffin & Bock, 2000; Spivey, Tanenhaus, & Eberhard, 2002). Significantly more studies have been conducted investigating comprehension processes than production, however, in part because up until recently, high resolution machines required minimal head and body movements. With the advent of more sophisticated equipment, such as head-mounted apparatus, it is now possible to investigate eye movements in conjunction with production of words and sentences, as well as other gross motor movements.

Eye tracking methodology has not yet been used to study the processes involved in rapid naming tasks, but studies investigating the connection between eye movements and production for simple noun phrases can elucidate some of the processes involved in RAN. Although object naming involves a strong semantic component which is largely absent in letter naming, both tasks involve the extraction of a phonological label from a visual stimulus (e.g., see Wolf & Bowers, 1999 and Levelt, Roelofs, & Meyer, 1999 respectively). Further, object naming studies have fortuitously measured the time line between eye movement duration (indicative of processing time) and production time when participants name sequences of two or more objects.

Results from these studies have clear implications for our understanding of the sequencing behaviour involved in RAN.

Meyer, Sleiderink, and Levelt (1998) presented participants with three line drawings of objects, with sufficient distance between items to prevent parafoveal processing. Participants tended to fixate only once on each object (for approximately 450ms) before moving their eyes (making a 'saccade') to the next item. Crucially, participants articulated the first object's name at about 800 ms; in other words, after the eyes had already moved on to the next stimulus, and this behavioural pattern in object naming is found to be robust (van der Meulen, 2001, 2003: see Figure 17 for a schematic of object naming). Speakers tend to make only one fixation on each item, and the eyes precede articulation of an object name by only one or two items. These findings suggest that speakers produce item names in an incremental fashion and complete a number of planning steps before executing a saccade to the next item.

Figure 17: The temporal order of eye and voice gestures when naming two objects.



In order to discover *which* planning steps are completed before moving the eyes to the next item, Meyer et al. (1998) conducted a number of manipulations to make the task more difficult: they taxed the visual system by presenting degraded line drawings, and increased the difficulty of retrieving object names by presenting objects with low-frequency labels (word frequency influences the retrieval rate of the morphological form of object names; e.g., Dell, 1990; Jescheniak & Levelt, 1994; Jescheniak, Meyer, & Levelt, 2003). Results showed that participants looked at an object for shorter intervals if its contours were intact and it had a high frequency name compared with conditions in which contours were degraded and the name was low-frequency. These findings suggest that in object naming, participants complete visuo-conceptual processing, select a lemma (a syntactic word representation), and retrieve the word's morphological form before shifting their gaze to the next item.

These findings were extended by Griffin (2001), who presented three objects, and varied the *codability* (the ease of selecting a lemma, based on how many different labels an object has (e.g., couch / sofa)) of the second and third items. Griffin found that only the frequency of the first item influenced speech onset of that item: neither frequency nor codability of subsequent items influenced first-item onset times. This finding suggests that the names of second and third items were selected only *after* onset of the first item. Moreover, Meyer and van der Meulen (2000) demonstrated that eye movements to a second object were only executed following access to the *phonological* as well as the morphological features of the object name. Participants showed shorter viewing times for objects when primed with an auditory stimulus with a similar phonological structure. Together, these findings are taken to suggest that processing the next item in an array does not occur before the phonological label of the previous item has been retrieved.

7.1.2 What can we infer with relevance to RAN?

The studies reviewed above suggest that naming a series of objects is an incremental process, which involves relatively sequential processing: a saccade is programmed to the next item only after phonological properties of the target item have been accessed. This serial naming style for objects is analogous to reading models such as the E-Z Reader (see Chapter 6) in which attention to the next item is only executed once processing of the fixated item is complete. In the studies reviewed, however, parafoveal processing was not possible, which may have encouraged the sequential processing styles observed. Henderson (1993) demonstrated that in visual scenes, some semantic information can be processed in the parafovea, allowing for the possibility that in more naturalistic situations, object preview might enable a more parallel processing style. Information processing (of either objects or letters) for production might therefore be accessed from the next item whilst simultaneously accessing features of the fixated item.

Further, although both object and letter naming involve accessing a phonological label via a visual representation, there are fundamental differences between the two tasks, which may influence processing style. Object naming, for example, involves a strong semantic component, which implicates retrieval of a lexical concept as opposed to a more arbitrary phonological label. Letter and digit naming, however, involve conversion of an arbitrary visual symbol into a phonological code, which largely bypasses semantic processing. Although reading text also involves retrieval of a lexical concept, naming alphaneumeric stimuli is considered a better indicator of *automatized* orthographic processing, thought to underpin fluent reading (Wolf & Bowers, 1999) than the more conscious access to semantic domains engendered by object and colour naming (Wolf & Obregon, 1992).

Whilst it is possible that eye-to-voice behaviour for letter naming would show a similar pattern compared with object naming, the processing stages involved in either task are therefore not identical and may lead to different naming behaviour. If sequential processing depends on executive load, for example, the relatively more straightforward (minimal semantic) access to letter names might allow a greater allocation of resources to processing the next item, perhaps before an advanced stage of processing the currently fixated ‘target’ item.

Finally, eye-voice behaviour for naming objects provides clues for investigating differences in RAN performance between dyslexic and non-dyslexic readers. Griffin

(2003), for example, suggests that shifting gaze to the next item in an array before articulation of the previous item benefits naming fluency compared with situations in which viewing and naming of objects is completed discretely. This suggestion is pertinent to our results from Experiment 1, in which non-dyslexic naming times were facilitated when more than one item was presented simultaneously. A possible source of reading group differences in naming, therefore, might be that dyslexic readers tend to process items in a more discrete style, thus producing less fluent naming. This hypothesis relates to our discussion in the previous chapter, in which we reviewed evidence by Chace et al. (2005) that dyslexic readers tend not to allocate attention to subsequent stimuli, presumably because the item currently under fixation is more difficult to process than for skilled readers. As such, it may be possible that dyslexic readers tend to articulate the foveated item before moving on to the next item, thus slowing naming times. In Chapter 6, we also considered an alternative suggestion that dyslexic readers tend to operate a more parallel processing style across graphemic items in the visual field (e.g., Pernet et al., 2006; Whitney & Cornelissen, 2005). Under this account, dyslexic readers do not operate a discrete processing style, but covert (and explicit– through saccades to the next item) attention to upcoming items in the visual field may interfere with production of the target name.

7.2 RAN as multi-tasking

Object naming studies using eye-tracking methodology are useful in that they provide a description of the behavioural interplay between eye-movements and articulatory gestures when naming items. However, the findings gleaned thus far provide only a rather simplistic account of the multiple processes that are executed when naming a series of items, many of which may occur in parallel. With reference to the RAN letters, Figure 18 provides a schematic of a ‘snapshot’ of the potential processing requirements involved in RAN at any moment in time. In addition to processing visual features and accessing appropriate phonological codes, RAN potentially involves three processes to handle upcoming and previous items: with reference to upcoming items, RAN may involve 1) activation of parafoveal information (as discussed in chapter 6), in addition to 2) programming a saccade to the next item before articulation of the target item. Further, we have hitherto concentrated on the effects of upcoming items, but what of the effects of previous items on RAN? An additional influence might therefore be 3) effectively suppressing representations of items already named. In the following sections, we detail the processes underlying the management of upcoming and previous items within the RAN.

Figure 18: Multi-processing requirements involved in RAN

Previous stimulus (n-1)	Target (n)	Next stimulus (n+1)
a	s	d

Note: In addition to naming the ‘target’ item (‘s’ in this example), RAN involves suppressing previously named information (‘a’) whilst activating information from the next item (‘d’).

7.2.1 Managing upcoming items

With reference to Figure 17, managing stimulus ‘n + 1’ or the ‘next’ stimulus in RAN whilst naming stimulus ‘n’ or the ‘target’ potentially involves parafoveal processing of the upcoming stimulus. The effect of preview on reading and RAN latencies was discussed at length in Chapter 6. In summary, preview of upcoming letters in text facilitates reading times (Balota & Rayner, 1983; McClelland & O’Reagan, 1981; Rayner, 1978, Rayner, McConkie, & Ehrlich, 1978; Rayner, McConkie, & Zola, 1980), and we propose that a similar mechanism may underpin naming times in RAN. Our previous attempts at investigating preview (Experiments 3 and 4) were arguably insufficiently sensitive to measure potential parafoveal effects. The eyetracking paradigm in this experiment, however, will allow us to measure naming times of specific confusable pairs within the context of the continuous RAN. The definition of a *preview effect* in this experiment will therefore be when naming is influenced by information in *n+1*, but the eye remains fixated on *n* (it has not yet saccaded to *n+1*).

Another possible effect of the *n+1* item on *n* naming times is when the eye is fixating on *n+1*. As we have seen from object naming studies, participants tend to view the next item whilst articulating the target. It is therefore possible that information from the next item might influence visual and phonological programming of the target stimulus. It should be noted, however, that if indeed the next stimulus alters target processing at the visual stage, there are two possible explanations of this occurrence. First, processing of information in *n+1* occurs before completion of visual processing stage of *n*. If this hypothesis is borne out, the finding will extend current findings from object naming studies to suggest that when naming serially presented *automatised* stimuli, features of the next item are activated before access to the phonological stage of the target item. Alternatively, processing of *n+1* does not commence until later stages (phonological access), but when it does begin, information processing of *n* can be revised in light of this new information. This scenario implies the possibility of feedback in lexical access, such as that predicted by Dell (1990). Our current paradigm does not allow us to distinguish between these alternatives, but either case would challenge Meyer et al.'s (1998) hypothesis that saccading to an *n+1* item implicates the completion of processing for the target *n*. Further, we may find that these processing styles differ for dyslexic and non-dyslexic readers.

7.2.2 Managing previous items

In contrast with upcoming items in RAN, the influence of previously named items on RAN latencies has not yet received a full discussion. However, the ability to suppress previously activated information in order to engage with the next item is arguably an important process for the efficient sequencing of items in the RAN. In this experiment, we will also measure the effect of inhibiting *n-1* or *previous* items on RAN latencies, but first we will discuss literature relating to executive control, suggesting why impaired ability to suppress information might contribute to the dyslexic naming speed deficit.

Inhibitory processes form part of the executive system in working memory (Pennington & Ozonoff, 1996), which controls attentional allocation to each of the slave systems (Baddeley & Hitch, 1974). Hari and Renvall (2001) propose that efficient allocation of attentional resources is critical in the ability to sequence visual and phonological information and so develop adequate representations of written verbal information. They propose that dyslexia involves *Sluggish Attentional Shifting* (SAS), which precludes rapid engagement and disengagement of attention. As a result of the prolonged time frame with which dyslexic readers shift their attentional resources, they have more difficulty processing Rapid Stimulus Sequences (RSS). As reviewed in Chapter 3, there is an abundance of data suggesting that dyslexic readers do not process perceptual information as quickly as average readers (e.g., Breznitz & Misra, 2003; Buchholz & Davies, 2005; Chase & Jenner, 1993; Facoetti, Lorusso, Cattaneo, Galli, & Molteni, 2005; Farmer & Klein, 1995; Greatrex & Drasdo, 1995; Helenius, Uutela, & Hari, 1999; Lehmkuhle, 1993; Lovegrove, 1993; Meyler & Breznitz, 2005; Overy, Nicolson, Fawcett, & Clarke, 2003; Stein & McAnally, 1995; Tallal, 1980; Tallal et al., 1993; Tallal, Merzenich, Miller, & Jenkins, 1993; Witton et al., 1998).

Hari, for example, (1995) demonstrated that dyslexic readers required significantly longer inter-sound intervals relative to controls in order to perceive an illusory auditory sample. Hari interpreted these results as indicative of a prolonged ‘cognitive integration window’ in dyslexia, in which there is more scope for successively presented sounds to interfere with one another. Evidence of multi-modal temporal processing deficits in dyslexia (Laasonen, Tomma-Halme, Lahti-Nuuttila, Service, & Virsu, 2000) also support Hari and Renvall’s (2001) hypothesis that RSS processing deficits reflect parietal lobe dysfunction, which aids attentional processing across all modalities. A modality-specific deficit is a potential but not exclusive means of impairing RSS performance, and any deficit that prolongs dyslexic readers’ cognitive integration window is a potential cause of poor RSS performance and concomitant reading deficits. Parietal abnormalities, for example, influence visuospatial attention, but can also produce visual, tactile and auditory neglect (Marshall, 2001), which can impede the development of connections between graphemes and their corresponding phonemes (e.g., Whitney & Cornelissen, 2005). Similarly, a motor deficit with concomitant articulatory impairments might disrupt the ability to establish clear phonological representations (e.g., Carlyon et al., 2001; Nicolson & Fawcett, 1990).

Findings also indicate that crossmodal judgements in particular are prolonged for dyslexic readers (Laasonen, Service, & Virsu, 2002), suggesting that attention plays an important role in integrating information from different modalities. In line with findings from low-level perceptual tasks, attentional factors are found to be strongly related to reading tasks requiring crossmodal processing. Thomson et al. (2005) revealed that some of the predictors of reading ability were affected by increased levels of inattention. Children with dyslexia in this experiment who also had comorbid levels of covert inattention obtained poorer performance on tasks measuring orthographic processing and rapid naming, but phonological coding factors for aural words was not affected. Thomson et al. claim that whereas orthographic processing involves cross-modal mapping of the stimulus' visual features in addition to accessing abstract phonological representations (e.g., Nobre, Allison, & McCarthy, 1994), decisions on phonological stimuli involve judgements only within the auditory system. (See Tanenhaus, Flanigan, & Seidenberg, 1980, for example, for evidence of orthographic representation activation in spoken word comprehension). Results by Thomson et al. (2005) are also consistent with findings demonstrating impaired visual processing speed in children with inattentive characteristics (Weiler, Bernstein, Bellinger, & Waber, 2002). Vidyasagar (2004), for example, proposed that attention processes mediate visual processing in order to operate a gating mechanism for serial processing of letters within words. This system is proposed to operate only indirectly on phonemic awareness via orthographic processing.

Attention deficits may therefore contribute to the naming speed deficit in dyslexia in a number of ways. One distal cause of a reduced ability to disengage from, or inhibit information within a narrow time frame may be a reduction in the quality of orthographic and phonological codes, which would slow recognition and production rates of letter items. The difficulty in disengaging attention from items already named might be a more direct cause of slowed naming latencies, however. Obregon

(1994), for example, proposed that longer pause times between items in the RAN may reflect a reduced ability to discontinue processing items in order to move onto the next item. Shifting attention from one item to the next might also prove particularly difficult in RAN if co-ordinating orthographic and phonological information has not become automatised (Wolf & Bowers, 1999). That is, an increased reliance on executive processes to integrate orthographic and phonological information from a particular letter item might augment the dyslexic readers' difficulty in shifting attention from that letter in order to begin processing the next item.

Experiment 5

The influence of previous and upcoming items on RAN latencies

6.3 Rationale and predictions

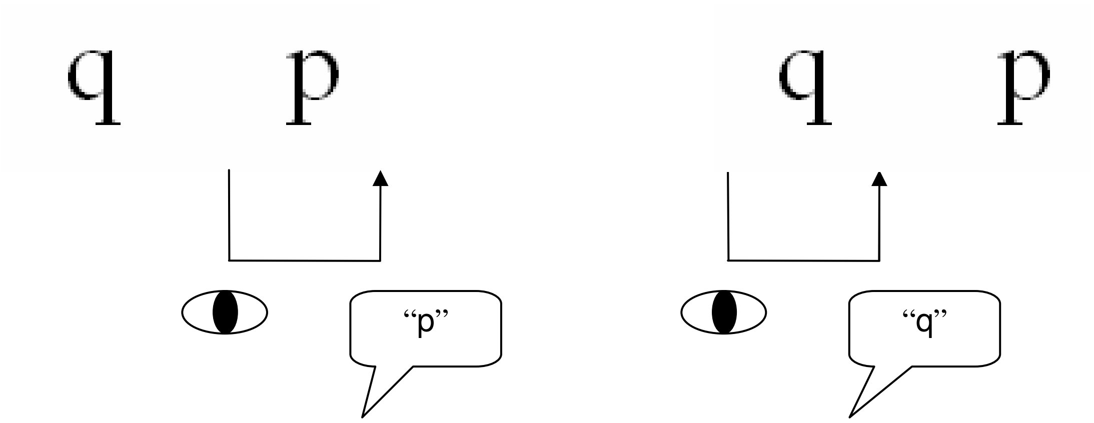
We suggest that continuous versions of RAN require participants to manage upcoming and previous letter information as well as processing the target stimulus in order to obtain fast latencies. Evidence from object naming studies suggests that sequencing items in order to name multiple objects involves accessing phonological features of the target name before attending to the next item. Processing the next item occurs whilst articulating the name of the target. Whilst these studies provide a starting point for investigating the interplay between eye movements and speech output in RAN, a number of additional factors require consideration. For example, the juxtaposition of items in normal reading conditions allows parafoveal processing. Further, a standardised RAN test is less than 2° of visual angle, which allows some preview of the upcoming stimulus. Similarly, object naming studies have tended not to investigate the effects of previous stimulus processing on target naming. In our view, good RAN performance involves efficient allocation of attentional resources, such that upcoming items are quickly activated and previously named items are suppressed. Preview of upcoming items may therefore comprise a critical role in RAN performance.

In this experiment, we use eyetracking methodology in order to investigate the qualitative features of naming for both dyslexic and non-dyslexic readers. We also measure the effects of previous and upcoming items on target naming times, and whether these effects are specific to visual or phonological domains. Experiment 5 is therefore a replication of Experiment 4 with some minor modifications and the use of more refined dependent measures yielded by the eyetracker. Experiment 5 again comprised visual in addition to phonological onset and rime letter sets, each with confusable versus non-confusable letter pairs. Each Letter set comprised a 2 (dyslexic vs. controls) x 2 (confusable vs. non-confusable pairs) design. In this experiment, however, we reverted to the full 50 items per trial in order to gain as much data as possible. Critically, we also included different letters in the visually confusable letter set (see the next section, this chapter). Following a pilot study, it was deemed that reversible letters (e.g. *p* and *q*) produced heightened confusability effects compared with the items used in Experiment 4.

In Experiment 5, we predicted that if items preceding and succeeding a ‘target’ (currently fixated) item in RAN influence naming latencies, then items in the confusable condition would yield longer latencies than items in the non-confusable condition. Further, these effects would be specific to the type of information processing pertinent to effective RAN performance (visual, or phonological onset / rime processing). If the RAN deficit in dyslexia involves a heightened processing deficit in either visual or phonological domains, we expected that the dyslexic group would show disproportionately longer naming times in the confusable conditions of the Letter set representing that domain. Thus far, our predictions follow a similar structure to that outlined in Experiment 4. In this experiment, however, we also attempted to parse the influence of *suppressing* previously named items from *activation* of upcoming items. To this end, we predicted that if good performance on RAN involves effective suppression of previous items, then naming times would be longer when confusable items preceded a target item; if good performance on RAN involves managing activated information from the upcoming stimulus, then naming times would be longer when confusable items succeeded a target item. If suppression of *n-1* or activation of *n+1* is pertinent to the RAN deficit in dyslexia, we expected that naming times would be disproportionately longer for the dyslexic group than controls under these conditions. This might also be reflected in participant gaze durations, indicating increased processing times.

We obtained three different measures from the eyetracking data in order to test these predictions. First, a *total time* measure of the time taken to read all 50 items per trial was obtained in order to compare the current findings with our measure in previous experiments. Second, we obtained an E*ye-Voice* span measure of target naming times (see Griffin & Bock, 2000). The *Eye-Voice* span is the time taken from the initial fixation on a stimulus to the speech onset of the item name. This measures the total processing time from when the eye begins receiving information from the stimulus, through to production of the item's name. For our purposes, we can measure how the length of the Eye-Voice span varies as a function of the confusability of items presented before and after the target item. Rather than being restricted to measuring pause times between articulatory signals, therefore (e.g. Obregon, 1994; Neuhaus et al., 2001), this measure allows us to establish the point at which the target stimulus is fixated and the length of time until it can be articulated. In order to measure the effects of suppressing the previous stimulus versus activating the next stimulus, the eye-voice span for either item in the letter pairs was considered, depending on the analysis (see Figure 19).

Figure 19: Eye-voice span measure in the *previous* and *next* visually confusable condition.



Note: In this example letter pair, the eye-voice span of target *p* is measured when *q* precedes the target. In a separate analysis, the eye-voice span of *q* becomes the target to measure the effect of upcoming stimulus *p*.

Third, we obtained a *processing time* measure, investigating the time spent fixating each letter. The processing time measure comprised two separate measures: a *total processing time* measure indicated the sum of all of the fixations spent on the target item, which included instances in which the eye either regressed to previous items or saccaded to items upstream in the array and came back to the target. A *current processing time* measure included the sum of fixations on a target item before the eye saccaded to the next item. This measure therefore disregarded regressive eye movements, but terminated once the eye fixated directly on the next (confusable or non-confusable) item in the array. These analyses aimed to elucidate whether the next item influences target processing time only after the next item has been directly fixated (*total processing time*), or whether the influence of the next item can be derived from parafoveal preview (*current processing time*).

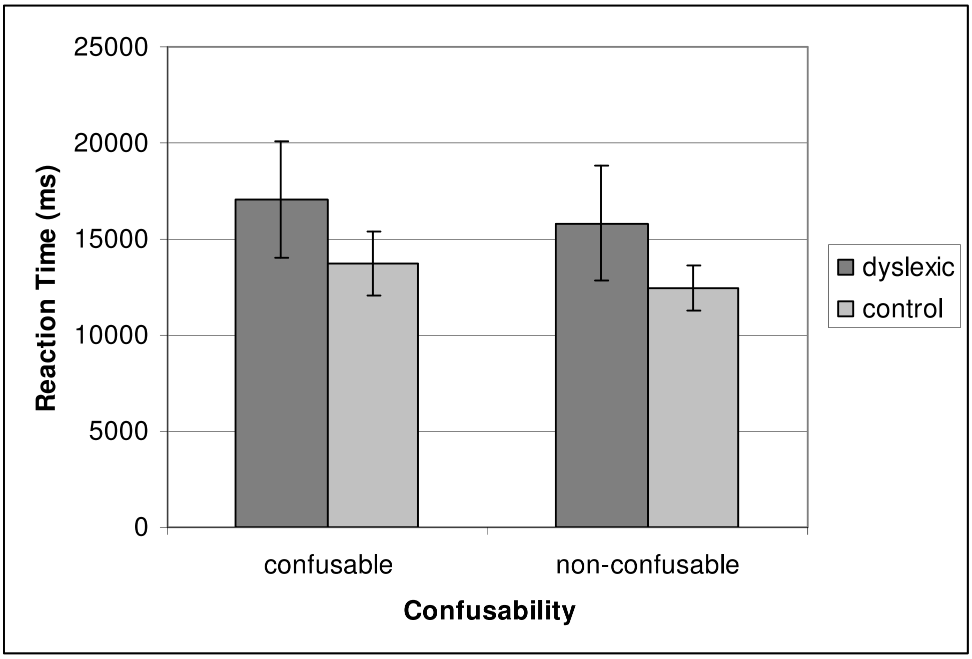
7.4 Pilot study

Before investing time in an eye-tracking experiment, however, we conducted a pilot study to assess whether the reversible letters chosen for the visually confusable items influenced participant naming times. Further, we wanted to assess whether changing the visual form of the letters by manipulating case (whilst keeping phonology constant) had any effect on naming times. Our rationale for selecting reversible letters is that although the majority of children have difficulty distinguishing these letters when learning to read (e.g., Davidson, 1935; Gibson, 1965), children with reading difficulties are known to find them much more confusable than their non-dyslexic peers (Kaufman, 1980; Terepocki, Kruk, & Willows, 2002) and a difficulty distinguishing these letters is a common indicator of dyslexia. Other researchers claim that these deficits do not cause young children's general difficulties with reversible letters (e.g., Liberman, Shankweiler, Orlando, Harris, & Bell-Berti, 1971; Snowling, 2000), but Whitney and Cornelissen (2005) suggest that letter reversals in dyslexia may comprise a visual-attention deficit. Apart from their orientation, reversible letters possess identical features. Invariant recognition of (e.g.) *b* can only be accomplished via higher activation (as a function of high visual acuity) of the straight, vertical segment in the left hemifield. In this way, *b* can be distinguished from ‘d’, whose curved segment is activated in the left hemifield. Thus, impaired left-to-right allocation of visual attention, even at the letter level can impede recognition.

A pilot study therefore investigated whether adjacent visually confusable (reversible) letters would yield longer RTs in general for adult readers compared with adjacent non-confusable letters (the same reversible letters, but in upper case). Eleven adult participants with dyslexia and 10 non-dyslexic controls participated in this pilot study. In a very similar design to Experiment 4, participants named 30 items in each trial, of which 8 were visually confusable, and 8 were visually non-confusable. Letter order within each pair was identical between the confusable and non-confusable trials, and within-condition letter orders were counterbalanced across trials. Presentation of confusable versus non-confusable was randomised across the session. The experiment lasted approximately 10 minutes.

Figure 20 shows that even in this relatively small sample, there is a robust effect for both groups, whereby confusable (lower case) items are slower to be named than non-confusable (upper case) items, and a two-way ANOVA (Group x Confusability) demonstrated that this was significant (*F* (1, 19) = 22.4, *p* < .001). The fact that phonological output was identical across conditions implies that these effects must be attributed to the visual form of the letters. We again found that dyslexics were slower than non-dyslexics (*F* (1, 19) = 10.9, *p* < .001). We did not find a Group-by-Confusability interaction (*F* = .01, *n.s.*), but this experiment is subject to the same criticisms as previous studies, in which summing RTs across the whole trial might obscure subtle differences in the way dyslexic and non-dyslexic groups respond to confusable items. We therefore decided to use reversible letters for our ‘visually confusable’ Letter set in the subsequent eyetracking experiment.

Figure 20: Group RTs across visually confusable and non-confusable letters.



7.5 Method

7.5.1 Participants

Two groups of 20 native British-English speaking students participated in this study. Groups comprised participants who had been formally assessed as dyslexic (10 males, 10 females) and a control group comprising participants who reported no difficulty with speech or literacy (11 females, 9 males). Mean ages were 23 years and 2 months (*SD* = 5.4) in the dyslexic group and 22 years and 1 month (*SD* = 4.1) in the control group, which were not statistically different (*t* = .41, *n.s.*).

7.5.2 Materials and Design

7.5.2.1 Cognitive and literacy tests

The cognitive profile tests in this experiment comprised similar core tests as those used in previous experiments: word recognition (Wide Range Achievement Test [WRAT-3]; Wilkinson, 1993), non-word and exception word reading (PATSy: Lum et al., 2001; Manis et al., 1996: see Appendix A and B) assessing phonological decoding and whole word recognition respectively and digit recall (Miles, 1993; assessing verbal short-term and working memory). However, we also included a measure of phonological *awareness*: Snowling (2000) proposed that the conscious manipulation of phonemes is a core feature of dyslexia, and we therefore include a spoonerism task in this experiment (Hatcher, Snowling, & Griffiths, 2002). Critically, we also assessed participants on verbal and non-verbal sections of the Wechsler Adult Intelligence Scale – 3rd edition (WAIS-III; Wechsler, 1992). In addition to ensuring minimal differences on non-verbal IQ, Goswami (2003) argued that group differences could also be caused by differences in verbal knowledge, such as vocabulary. To ensure no such confounds, we therefore administered the Vocabulary as well as Block Design sections of the WAIS. WRAT-III spelling takes 20 minutes itself and was not therefore included in order that the battery was not too tiring.

7.5.2.2 Experiment

In the experimental sessions, Confusability (confusable, non-confusable) was manipulated in each Letter set (Visual, Onset, Rime) and Letters in the phonological onset and rime conditions were identical to those used in Experiment 4: Onset items comprised (g – j (onset /dʒ/); k – q (onset /k/)), whilst Rime items included (b – v (rime /i/); j – k (rime /eI/)). Letters in the Visual set, however, included new items: the pilot study reported above demonstrated that reversible letters showed a tendency to be confusable when presented adjacently, and are therefore used in this experiment. Confusable items comprised (p – q; b – d). In each set, the fifth letter was the filler item (z). Each letter appeared 10 times in each continuous trial, and items were manipulated for confusability: phonological items were presented adjacently in order to promote confusability (Onset: (g – j; k – q; Rime: b – v; j – k) or non-adjacently to minimise confusability (Onset: g – k; j – q; Rime: b – k; v – j). Visual items were presented in the same order across confusable vs. non-confusable trials, but confusability was manipulated via the letter case: confusable items were presented in lower case (p – q; b – d) whilst non-confusable items included identical letters but in upper case (P – Q; B – D). In this way it was possible to vary the visual presentation whilst controlling for the effects of phonology. The potential of confounding the results with items that had similar rimes (b – d) was therefore minimised. In order that a confusability effect in the visual condition could not be attributed to letter case, letters in the phonological sets were also upper case on half of the trials (between-participants). The experiment yielded a 2 (dyslexic vs. control) x 2 (confusable vs. non-confusable) design for the Rime, Onset and Visual Letter sets.

7.5.3 Procedure

7.5.3.1 Cognitive and literacy tests

The cognitive and literacy tests in this experiment took approximately 40 minutes to administer and the order in which participants completed the tests was determined by a Latin square design. Participants also alternated in terms of whether they completed the experimental session or the cognitive tests first.

7.5.3.2 Experiment

For the experimental sessions, participants sat approximately 60cm from a 21” monitor running at 120Hz. They wore an SR-Research EyeLink-II head-mounted eye-tracking system with a sampling rate of 500 Hz and a spatial resolution of less than 0.01°. Participants viewed the screen binocularly, but movements were recorded from only one (dominant) eye. Head movements were not restricted, but participants were asked to keep them to a minimum. The eyetracker recorded onsets and offsets of fixations (defined by acceleration and velocity thresholds) and corresponding pixel coordinates. The experiment began with adjustment of the infrared cameras attached to the eyetracker, followed by a brief calibration procedure. Participants were required to view crosses in 12 different locations, and the recalibration procedure was repeated throughout the experiment whenever measurement accuracy was deemed insufficient (e.g., when the participant made a gross head movement).

Each trial in the experiment began with a drift correction (comprising a small circle) in the same position as the first letter to be named (top left hand corner of the screen). When the participant’s eye was on the circle, the experimenter pressed a button to present the trial. Letters were presented in Arial 18 point font at a character size of 1°, with 2° between each letter. Participants were instructed to name the letters as quickly as possible and to begin naming as soon as the letter array appeared. They pressed a button to indicate that they had finished naming (to terminate the trial). The experiment was also self paced, such that participants initiated each trial. Participants' spoken output was recorded on the PC via an ASIO sound card: recording began automatically at the beginning of the trial and terminated at the end of the trial. Letter sets and confusable / non-confusable trials were randomised across the experiment to avoid practice effects with similar items. Each session lasted approximately 30 minutes.

7.6 Data analysis and results

7.6.1 Cognitive and literacy tests

Overall, the dyslexic group demonstrated significantly poorer performance on single word reading measures (word, non-word and exception word reading measures). Phonological awareness was also more impaired in the dyslexic group relative to controls (measured by performance on the Spoonerisms task). We also found that the dyslexic group demonstrated poorer performance on the WAIS Vocabulary task, allowing for the possibility that this difference might influence group differences on our experimental RAN tasks (see Table 17). Two participants in the dyslexic group obtained RAN scores that were 1.5 SDs lower than the non-dyslexic average and their error counts on the non-word reading and spoonerisms tasks were lower than the non-dyslexic mean. They also showed scores that were 1.5 SDs below the non-dyslexic mean on Non-Verbal IQ. Their data was therefore more consistent with a so-called *garden-variety* profile rather than a profile characteristic of dyslexia and their data was excluded from the analysis.

Table 17: Reading group scores on reading measures, verbal memory and IQ.

		Dyslexic	Non-dyslexic	*T*	Cohen's *d*
Word Reading	Mean	100.62	113.97	4.1***	1.33
	SD	12.65	6.44		
Non-word reading	Mean	5.73	1.58	3.4**	1.06
	SD	5.46	1.86		
Spoonerisms	Mean	6.38	2.34	2.4*	0.73
	SD	6.71	3.65		
Exc.-word reading	Mean	4.95	2.22	3.5***	1.23
	SD	2.26	1.37		
Forward digit span	Mean	9.35	10.24	1.5	0.47
	SD	2.19	1.71		
Backward digit span	Mean	3.68	4.39	1.2	0.37
	SD	1.93	1.85		
WAIS-Vocabulary	Mean	12.7	13.1	2.6*	0.15
	SD	2.7	2.4		
WAIS-Block design	Mean	10.1	11.1	0.3	.09
	SD	1.0	1.2		

Note. * $p < .05$; ** $p < .01$; *** $p < .001$. Word reading = standardised scores; non-word reading and exception word reading = errors /44 and /45 respectively, spoonerisms = errors /24; Verbal memory = errors: Forwards digit span = /12; Backwards digit span = /6 points. WAIS = scaled scores.

Further, the group difference in Verbal IQ (vocabulary) suggests that members of the dyslexic group have had less experience with orthography than members of the non-dyslexic group (e.g., Stanovich, 1986). To ensure that our results were not attributable to differences in verbal IQ, we covary this factor in the analyses described in the following section.

7.6.2 Reaction Times

The spatial fixation coordinates from the eyetracking output were defined as regions of interest. A region of interest corresponding to each letter comprised 96 pixels horizontally (such that the centre of each letter comprised the midpoint, and the region extended to precisely half way between letters). The letter area comprised 15 pixels of this region. Using this region, we could determine when, with reference to a zero point representing the beginning of the trial, the participants' gaze entered each region (corresponding to a particular letter) and how long the participant stayed in each region before saccading to the next region. Extremely short fixations (below 80ms) and short fixations succeeding a longer fixation but lying within 0.5° of visual angle were pooled. Very short fixations are normally associated with false saccade programming and are unlikely to reflect information processing (e.g., Rayner & Pollatsek, 1989).

The times at which speech onsets occurred (onsets of each letter item) were obtained using professional sound editing software and were measured relative to the same zero point as the eye-fixation data. Onsets were determined using a script which recorded an onset when the sound wave reached a specified intensity. Correct responses were matched to the relevant eye fixation data in order to calculate eye-voice spans for each letter. Approximately 7% of the data was excluded (including technical faults, participant error and exclusion of two participants).

Three reaction time measures were calculated: First, a *total time* measure, comprising the time taken from the beginning of the trial to the voice onset of the 47th letter. (A simple measure of fixation counts for each participant across all trials revealed that the 47th letter, of the 45th – 50th letters - was the least likely to be skipped). Second, an *Eye-voice* span measured the time between the first fixation on a letter to the onset of the letter name. Third, a *processing time* measure investigated the time spent fixating each letter was measured. The processing time measure comprised two separate measures: a *total processing time* measure indicated the sum of the total number of fixations spent on the target item, which included instances in which the eye either regressed to previous items or saccaded to items upstream in the array and came back to the target. A *current processing time* measure included the sum of fixations on a target item before the eye saccaded to the next item. This measure was similar to first pass reading measures used in the reading literature (e.g., Rayner, 1998), in that it terminated once the eye fixated directly on the next (confusable or non-confusable) item in the array. However, whereas regressive movements from the critical region were discounted, fixations that returned to the region after such a regression were included in the measure..The *Eye-voice span* and *processing time* measures included only correctly named items that were preceded or succeeded by a confusable item or its non-confusable equivalent.

We used Linear Mixed Effects (LME) models to analyse the data. LME is particularly useful for analysing data from heterogeneous groups (such as groups with dyslexia), and this analysis allowed us to separate the variance contributed by participants and items from confusability effects. Because participant and item variability are partialled out, therefore, there is no need to do separate by-participant and by-items analyses. LME models are similar to ANOVA in that both indicate the effect of fixed-effect variable(s) on the dependent variable. The methods for establishing differences between manipulations differ between LME and ANOVA, however: in ANOVA, differences between experimental conditions are compared with reference to the differences between their respective mean values and standard deviations from these means. In LME, on the other hand, group differences are based on whether the amount of variance contributed by one condition of the variable is significantly greater than the amount contributed by another condition of the variable.

In the current experiment, for example, there are two independent variables (Group and Confusability), each with two conditions (dyslexic, non-dyslexic; confusable, non-confusable). Briefly, we predict that RTs for dyslexic readers will differ from RTs for non-dyslexic readers, and RTs for confusable items will differ significantly from non-confusable items. The baseline for our analysis is therefore non-dyslexic – non-confusable trials. We then assess whether the amount of variance contributed by other conditions of the variables (dyslexic – non-confusable and non-dyslexic – confusable) differ significantly from this baseline. These comparisons therefore serve as our main effects analyses. (Note that in LME, the within-participants Confusability main effect is established on the basis of only the non-dyslexic group). Whether or not a Group x Confusability interaction exists depends on the final variable entered into the model, dyslexic – confusable trials in this experiment. If the variance in this group significantly exceeds the sum of the variance of the conditions previously entered into the model (non-dyslexic – non-confusable, dyslexic – non-confusable and non-dyslexic – confusable), there is evidence of an interaction between the variables.

In this experiment, factors with higher sum-of-squares values were entered first into the model, since those factors had higher variability. LME analyses were conducted with and without the covariate *Vocabulary score*. In general, Vocabulary did not contribute significant variance to the data, suggesting that it could not account for group differences. We therefore give priority to analyses with no covariate, but in order to be thorough, we subsequently report how including a covariate influenced the pattern of results.

7.6.2.1 Confusability and total naming time (per trial)

The total naming time coefficients (across the 4 trials in each condition) for confusable versus non-confusable trials in each of the Rime, Onset and Visual Letter sets are displayed in Table 18 and Figures 21, 22, and 23.

Table 18: Group coefficients (ms) on total trial times as a function of confusability across Rime, Onset and Visual Letter sets.

	Dyslexic		Non-dyslexic	
	Conf	Nonconf	Conf	Nonconf
Rime	28680	22954	22770	22564
Onset	34737	25626	26736	25250
Visual	30637	21918	23355	21019

Figure 21: Group coefficients and 95% confidence intervals on total trial times as a function of confusability in the Rime Letter set.

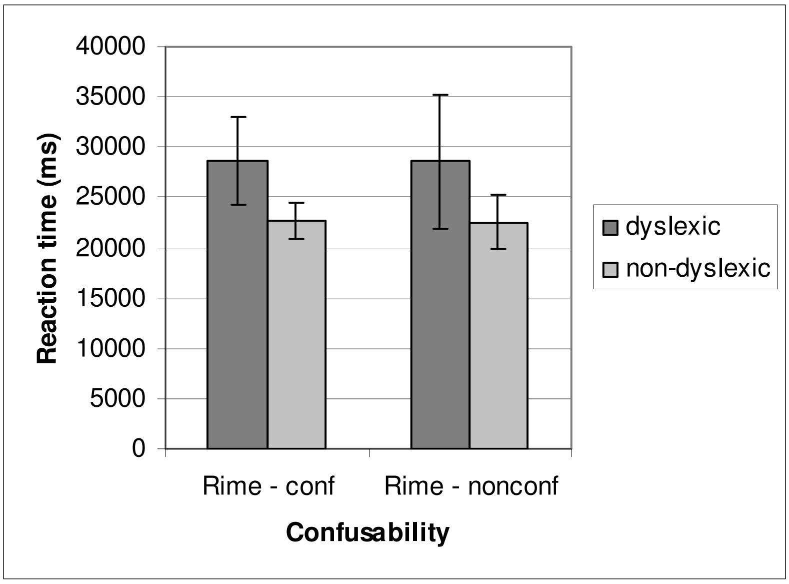


Figure 22: Group coefficients and 95 % confidence intervals on total trial times as a function of confusability in the Onset Letter set.

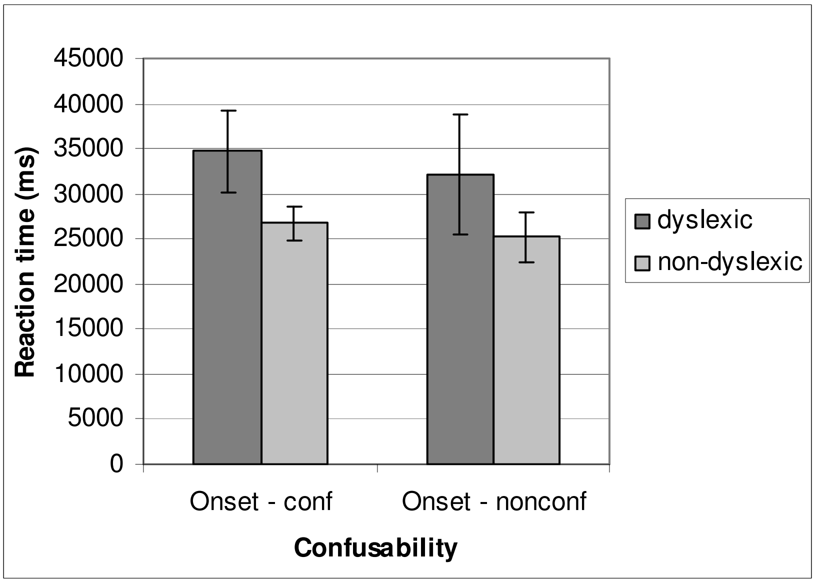
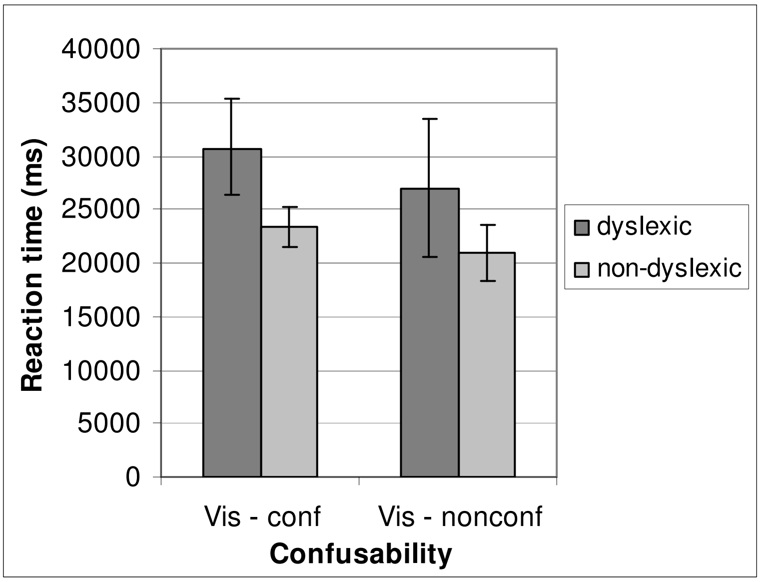


Figure 23: Group coefficients and 95 % confidence intervals on total trial times as a function of confusability in the Visual Letter set.



An LME analysis, with the factors Group and Confusability was conducted for each Letter set. In the analyses reported below, the non-dyslexic non-confusable trials form the baseline condition. The amount of variance contributed by the dyslexic non-confusable trials is then compared to this condition. Then, the variance contributed by the non-dyslexic confusable trials is also compared to the baseline. Finally, the variance contributed by the dyslexic confusable trials is compared to the three other conditions entered into the model in order to investigate the existence of an interaction.

In the Rime Letter set, the dyslexic group yielded slower latencies than non-dyslexics in the non-confusable condition (t = 4.55, p < .0001). The non-dyslexic group showed no difference in performance on the confusable versus the non-confusable condition, however (t = 0.45, *n.s.*) and no interaction emerged (t = 0.27, *n.s.*).

In the Onset Letter set, the dyslexic group again yielded slower latencies compared with the non-dyslexic group in the non-confusable condition (t = 6.0, p < .0001). Further, the non-dyslexic group were slower on the confusable condition than on the non-confusable condition (*t* = 3.31, *p* < .01), and a marginal interaction emerged, such that the dyslexic group were significantly slower relative to the non-dyslexic group on the confusable condition compared with the non-confusable condition (*t* = 1.7, *p* = .09).

In the Visual Letter set, the dyslexic group were slower on the non-confusable condition than the non-dyslexic group (*t* = 5.59, *p* < .0001). The non-dyslexic group were slower on the confusable condition than on the non-confusable condition (*t* = 5.79, *p* < .0001). Further, an interaction emerged, such that the dyslexic group were significantly slower relative to the non-dyslexic group on the confusable condition compared with the non-confusable condition (*t* = 2.42, *p* < .05).

Recall that in the cognitive and literacy tests, WAIS-III yielded a significant group difference on verbal IQ. Vocabulary was therefore entered into the model (before the other conditions) in order to investigate whether this variable could account for the group differences observed in the experimental manipulations. Vocabulary did not contribute additional variance to the models in Rime and Onset Letter sets (*t* = 1.64, *n.s.*; *t* = 1.39, *n.s.*), but it contributed with marginal significance to the Visual Letter set analysis (*t* = 1.95, *p* = .052). The inclusion of Vocabulary in the model did not alter the pattern of results in any of the analyses, however, suggesting that performance on this measure cannot explain reading group differences on the RAN.

In sum, we found that confusable Rime items did not influence trial naming times for either group. In contrast, confusable Onsets and Visual information yielded longer latencies for both groups, but dyslexic readers in particular. These results suggest that both phonological and visual information influence rapid naming, and hence reading fluency. Our measure of the total time to name the items within trials is comparable to the measure used in previous experiments. In the following sections, we investigate the validity of the current results by examining the effects of confusability within pairs of letters (thus excluding errors and irrelevant items within each trial).

7.6.2.2 Confusability and Eye-Voice span (per letter)

The variable Eye-Voice span measured the time from the initial fixation on a letter to the onset of the letter name. However, the distribution of responses was different between groups: the dyslexic group showed a more negatively skewed distribution, so the variable was logged in order to normalise the distribution. Eye-Voice span was therefore measured as a function of Group (dyslexic, non-dyslexic) and Confusability (confusable, non-confusable) in separate analyses. First, an analysis ascertained the effects of a confusable letter presented immediately before the target on the target's eye-voice span (PREV). A second analysis investigated the effects of presenting a confusable letter immediately after the target (NEXT). These analyses were conducted for Visual, Onset and Rime Letter sets respectively. Analyses are reported in the same order as the total trial times: main effects of Group and Confusability are considered before the interaction effect. Tables 19 and 20 and Figures 24 - 29 represent the coefficients of Eye-Voice span values for target items.

Table 19: Group coefficients (ms) of target Eye-Voice spans in the confusable and non-confusable condition. Results from Rime, Onset and Visual Letter sets in the PREV analyses.

	Dyslexic		Non-dyslexic	
	Conf.	Nonconf.	Conf.	Nonconf.
Rime	671	666	607	602
Onset	745	717	726	699
Visual	641	637	621	617

Table 20: Group coefficients (ms) of target Eye-Voice spans in the confusable and non-confusable condition. Results from Rime, Onset and Visual Letter sets in the NEXT analyses.

	Dyslexic		Non-dyslexic	
	Conf.	Nonconf.	Conf.	Nonconf.
Rime	683	697	619	632
Onset	740	724	697	681
Visual	709	689	675	656

Figure 24: Group coefficients and 95 % confidence intervals as a function of Confusability in the PREV – Rime analysis.

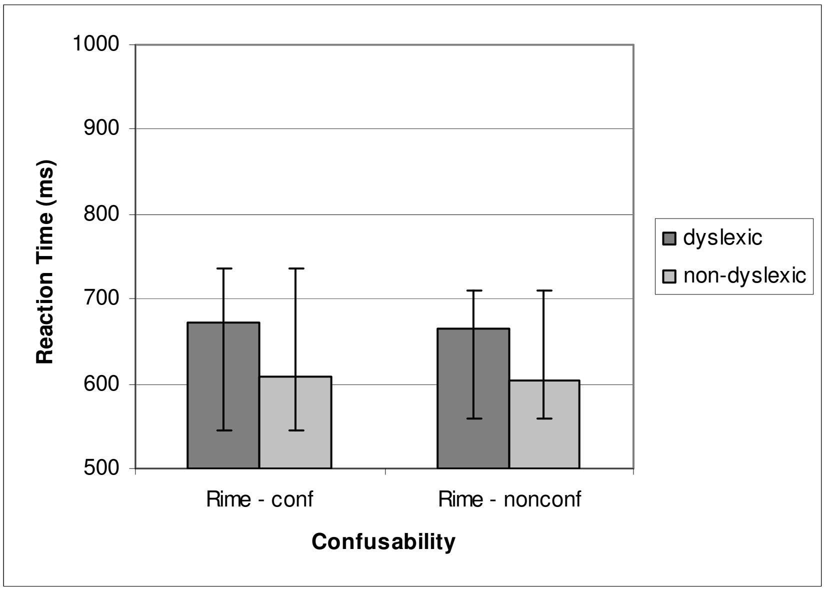


Figure 25: Group coefficients and 95 % confidence intervals as a function of Confusability in the PREV – Onset analysis.

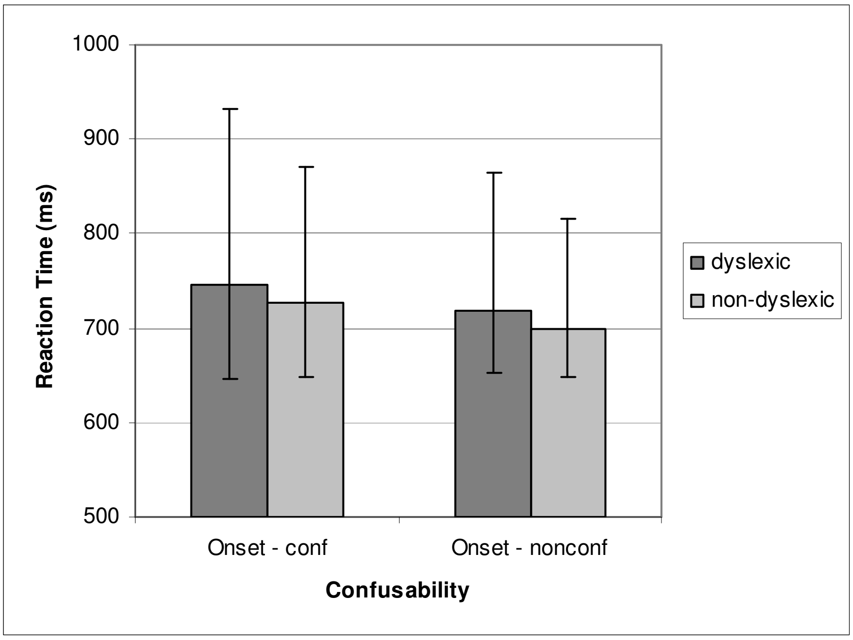


Figure 26: Group coefficients and 95 % confidence intervals as a function of Confusability in the PREV - Visual analysis.

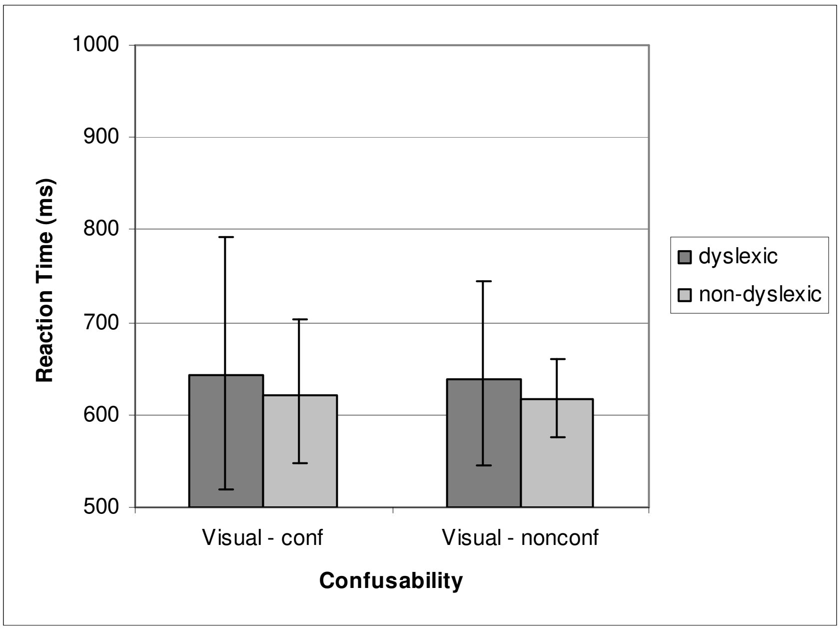


Figure 27: Group coefficients and 95 % confidence intervals as a function of Confusability in the NEXT – Rime analysis.

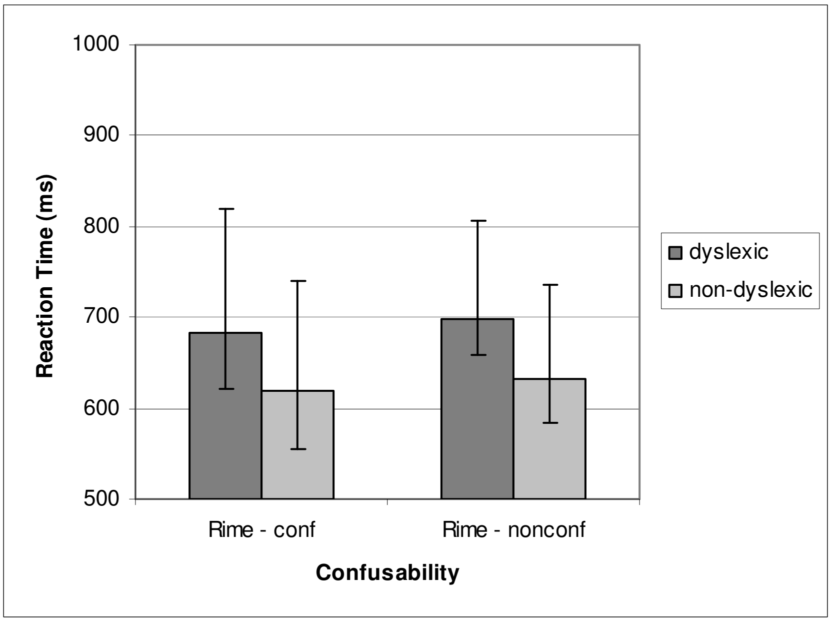


Figure 28: Group coefficients and 95 % confidence intervals as a function of Confusability in the NEXT – Onset analysis.

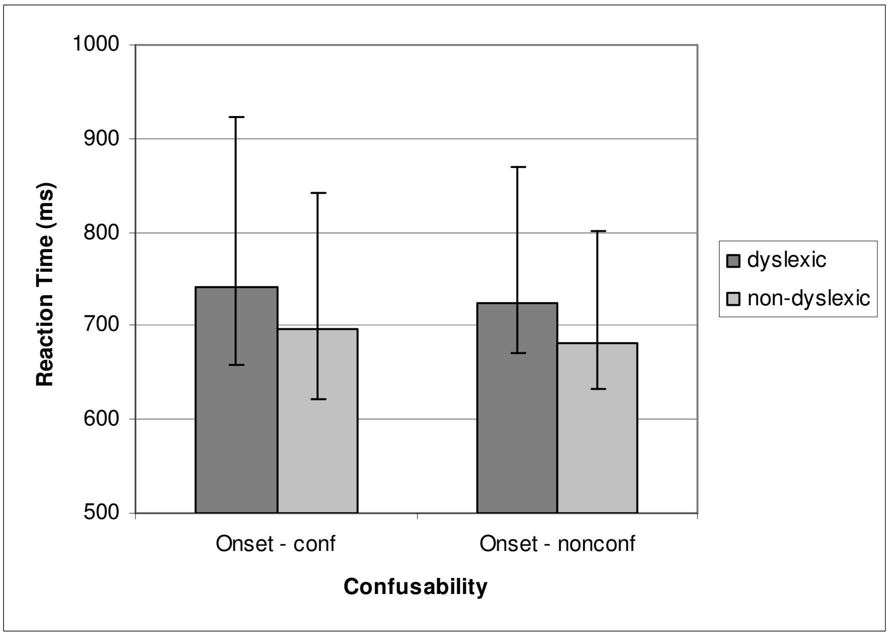
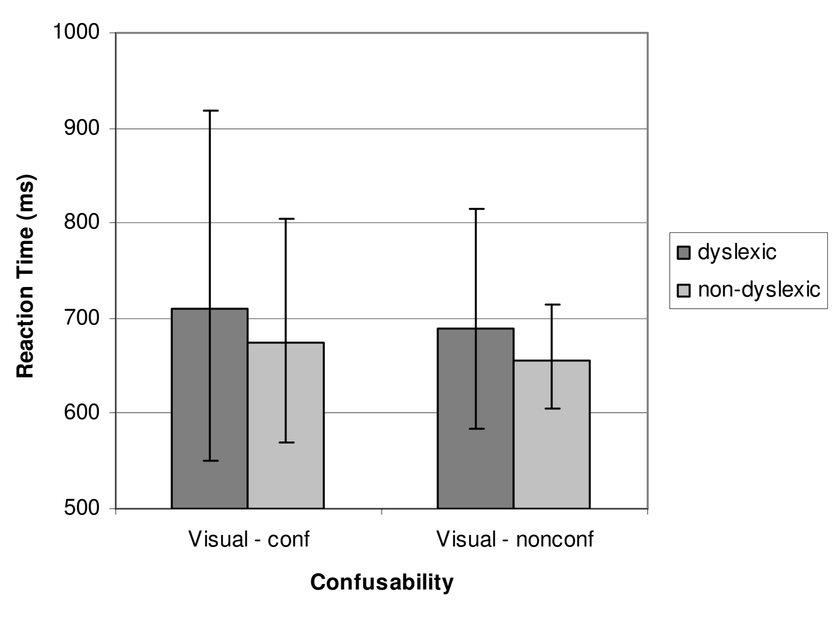


Figure 29: Group coefficients and 95 % confidence intervals as a function of Confusability in the NEXT - Visual analysis.



In the Rime analyses, the dyslexic group yielded slower latencies than the non-dyslexic group in the non-confusable condition (PREV: *t* = 1.98, *p* < .05; NEXT: *t* = 2.07, *p* < .05). The non-dyslexic group's Eye-Voice span was not influenced by confusable Rimes in either position, however (PREV: *t* = .47, *n.s.*; NEXT: *t* = 1.23, *n.s.*) and no interaction emerged (PREV: *t* = 1.12, *n.s.*; NEXT: *t* = 0.69, *n.s.*).

In the Onset analyses, there was no significant difference between the dyslexic and non-dyslexic group in the non-confusable condition. (PREV: *t* = .47, *n.s.*; NEXT: *t* = 1.18, *p* n.s.). Non-dyslexic readers' Eye-Voice spans were significantly longer in the confusable compared with the non-confusable condition in *previous* analysis (PREV: *t* = 1.94, *p* < .05), but this was not the case in the *next* analysis (NEXT: *t* = 1.14, *n.s.*). An interaction emerged in both analyses, such that the dyslexic group yielded higher Eye-Voice spans relative to the non-dyslexic group in the confusable compared with the non-confusable condition (PREV: *t* = 3.75, *p* < .0001; NEXT: *t* = 2, *p* < .05).

In the Visual analyses, dyslexic and non-dyslexic readers yielded non-significant differences in the non-confusable condition (PREV: *t* = .77, *n.s.*; NEXT: *t* = .1.17, *p* n.s.). However, non-dyslexic performance did not differ significantly on the confusable compared with the non-confusable condition (PREV: t = .23, *n.s.*; NEXT: t = .67, p n.s.). Both analyses yielded a significant interaction, such that the dyslexic group obtained longer Eye-Voice spans in the confusable condition compared with the non-confusable condition (PREV: t = 3.35, p < .0001; NEXT: t = 3.65, p < .0001).

The inclusion of the Vocabulary variable in the LME model did not contribute significant variance to Eye-Voice span in any of the analyses (Rime (PREV): t = .71, *n.s.*; Rime (NEXT): t = .97, *n.s.*; Onset (PREV): t = .45, *n.s.*; Onset (NEXT): t = .66, *n.s.*; Visual (PREV): t = .78, *n.s.*; Visual (NEXT): t = .68, *n.s.*).

In sum, our results from the Eye-Voice span analyses suggest that confusable Rime items did not influence either group. Confusable Onset items, on the other hand yielded longer latencies for non-dyslexics when presented before the target, suggesting a difficulty suppressing previous information, and perhaps implicating the articulatory loop (see Discussion, this chapter). Our results also suggest that processing times (Eye-Voice span) for target items were longer in the dyslexic group when confusable onsets preceded and succeeded the target item. Critically, confusable visual information did not influence processing time for the non-dyslexic group, but it yielded longer processing times for dyslexics when items preceded and succeeded the target.

7.6.2.3 Confusability and processing time (per letter)

The variable *processing time* was investigated in two separate analyses. *Total processing time* comprised the total duration (the sum of the durations of all the fixations) that the eye spent fixating each letter (including regressions back to the same letter). *Current processing time* included only the sum of fixations on the target letter before the eye saccaded to the next letter. Our primary interest was whether confusable information in the NEXT position would influence target processing times in both analyses (an effect in the current processing time analyses would signify preview effects of the next item) or whether we would only find an effect in the total processing time analyses (implying that confusability imposed on the target letter by the next item in the array occurred as a function of the measure's inclusion of explicit saccades to the next item and regressions back to the target). As with the Eye-Voice span analyses, both processing time variables were negatively skewed, so they were logged in order to normalise the distribution. Total processing time and current processing time were measured as a function of Group (dyslexic; non-dyslexic) and Confusability (confusable; non-confusable) in separate analyses. Analyses ascertained the effects of presenting a confusable letter after the target (NEXT). Table 21 and Figures 30, 31 and 32 represent the coefficients of *total* processing times for target items. Table 22 and Figures 33, 34, and 35 represent the coefficients of *current* processing times for target items.

Table 21: Group coefficients for total processing time (ms) across Confusability in each Letter set.

	Dyslexic		Non-dyslexic	
	Conf	Nonconf	Conf	Nonconf
Rime	445	458	369	380
Onset	592	508	416	405
Visual	539	480	434	373

Figure 30: Group total processing time coefficients and 95 % confidence intervals in the confusable and non-confusable condition in the Rime Letter set.

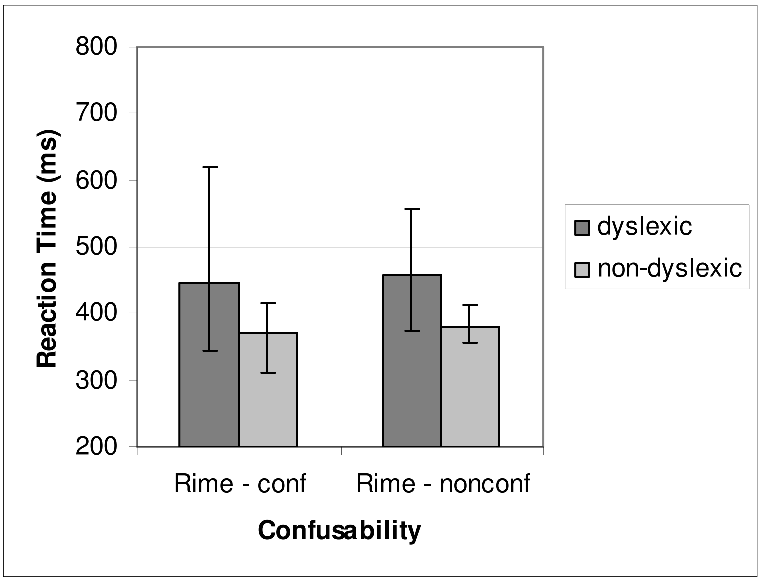


Figure 31: Group total processing time coefficients and 95 % confidence intervals in the confusable and non-confusable condition in the Onset Letter set.

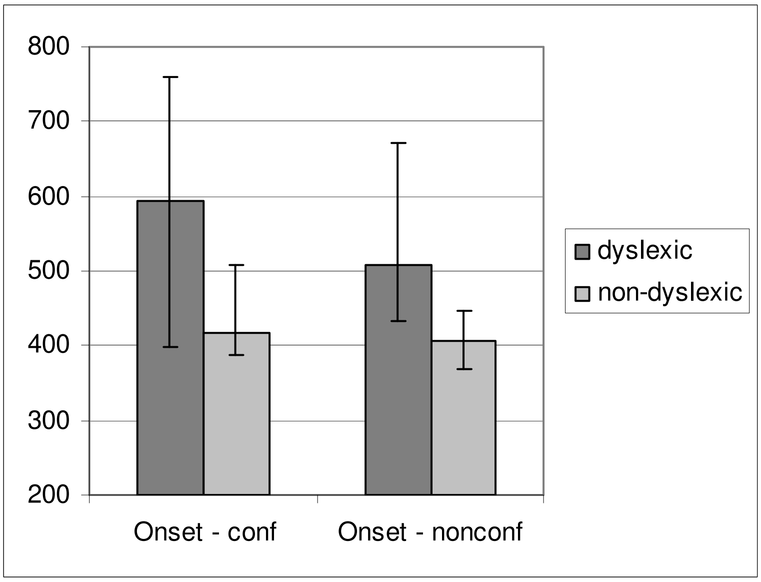
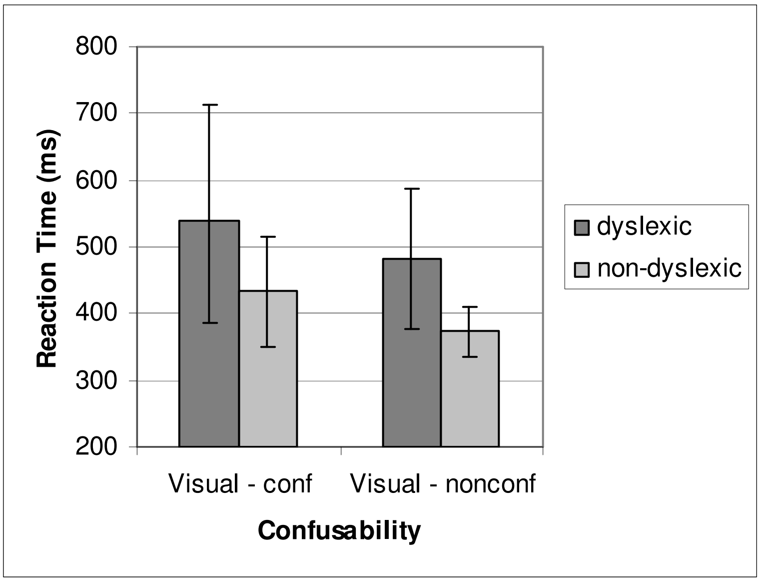


Figure 32: Group total processing time coefficients and 95 % confidence intervals in the confusable and non-confusable condition in the Visual Letter set.



The *total processing time* analyses yielded the following results: In the Rime Letter set, the dyslexic group yielded slower latencies compared with the non-dyslexic group in the non-confusable condition (*t* = 3.24, *p* < .01). The non-dyslexic group did not show a significant difference on the confusable condition relative to the non-confusable condition (*t* = 1.45, *n.s.*), and no interaction emerged (*t* = 1.29, *n.s.*).

In the Onset Letter set, the dyslexic group was also found to yield slower latencies than the non-dyslexic group in the non-confusable condition (*t* = 4.7, *p* < .0001). Further, the non-dyslexic group demonstrated longer latencies on the confusable compared with the non-confusable condition (*t* = 4.12, *p* < .001). Critically, an interaction also emerged: the dyslexic group yielded disproportionately slower latencies than the non-dyslexic group in the confusable condition compared with the non-confusable condition (*t* = 2.36, *p* < .05).

In the Visual Letter set analyses, the dyslexic group yielded longer latencies compared with the non-dyslexic group in the non-confusable condition (*t* = 3.9, *p* < .001). Further, the non-dyslexic group yielded longer latencies in the confusable condition compared with the non-confusable condition (*t* = 3.16, *p* < .01). Although there was a trend in the Visual Letter set similar to the interaction in the Onset Letter set, this finding was not significant ($t = 1.51$, *n.s.*).

Vocabulary contributed marginally significant variance to total processing time in the Rime ($t = 1.55$, $p = .06$) and Onset ($t = 1.67$, $p = .09$) Letter set analyses, and contributed significant variance in the Visual analysis ($t = 2.3$, $p < .05$). The addition of Vocabulary as a variable in these analyses did not influence the pattern of results in any of the Letter sets, however.

In the *current processing* time analyses, a similar pattern of results was found as in the total processing time analyses. In the Rime Letter set, the dyslexic group were slower on the non-confusable condition relative to the non-dyslexic group ($t = 3.16$, $p < .01$). The non-dyslexic group showed no significant difference in performance on the confusable versus the non-confusable condition ($t = 1.53$, *n.s.*), and no interaction emerged ($t = 1.43$, *n.s.*).

In the Onset Letter set, the dyslexic group yielded longer latencies compared with the non-dyslexic group in the non-confusable condition ($t = 4.6$, $p < .0001$) and the non-dyslexic group yielded longer latencies on confusable compared with the non-confusable condition ($t = 3.54$, $p < .001$). An interaction emerged as in the total time analyses: the dyslexic group was disproportionately slower in the confusable compared with the non-confusable condition ($t = 2.70$, $p < .01$).

An identical pattern of results as that found in total processing times was also found in the Visual Letter set: the dyslexic group yielded longer latencies compared with the non-dyslexic group on the non-confusable condition ($t = 3.71$, $p < .001$). Further, the non-dyslexic group yielded longer latencies on confusable compared with the non-confusable condition ($t = 2.75$, $p < .01$). Again, despite the trend in Figure 32, the dyslexic group were not significantly slower in the confusable condition compared with the non-confusable condition ($t = 1.28$, *n.s.*).

Table 22: Group coefficients for *current processing* duration (ms) across Confusability in each Letter set.

	Non-dyslexic		Dyslexic	
	Conf	Nonconf	Conf	Nonconf
Rime	369	368	424	452
Onset	411	388	557	504
Visual	428	361	507	475

Figure 33: Group current processing time coefficients and 95 % confidence intervals the in confusable and non-confusable condition in the Rime Letter set.

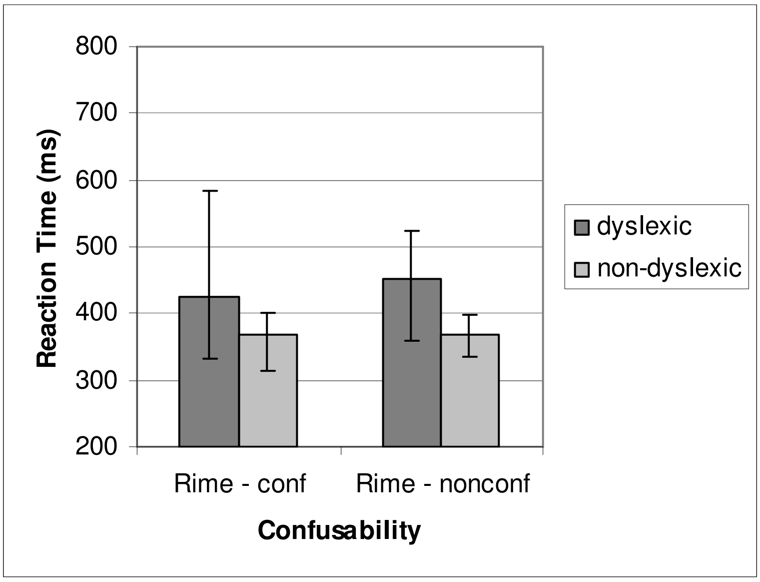


Figure 34: Group current processing time coefficients and 95% confidence intervals in the confusable and non-confusable condition in the Onset Letter set.

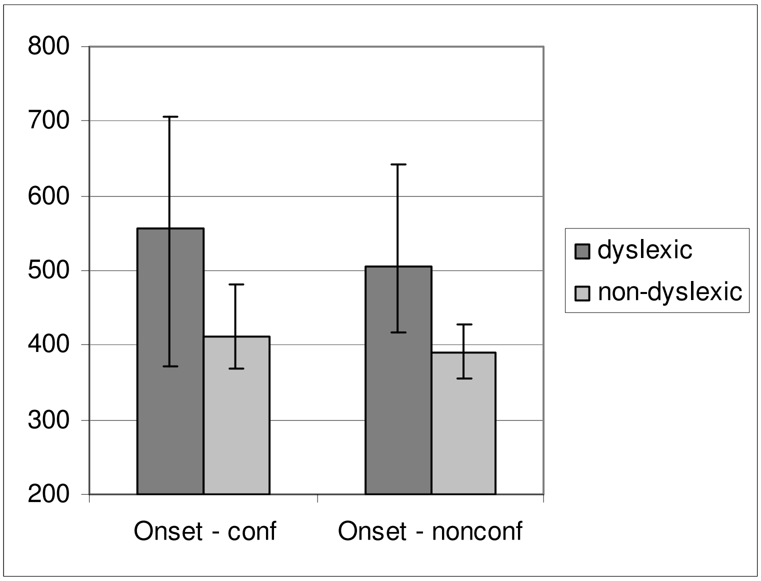
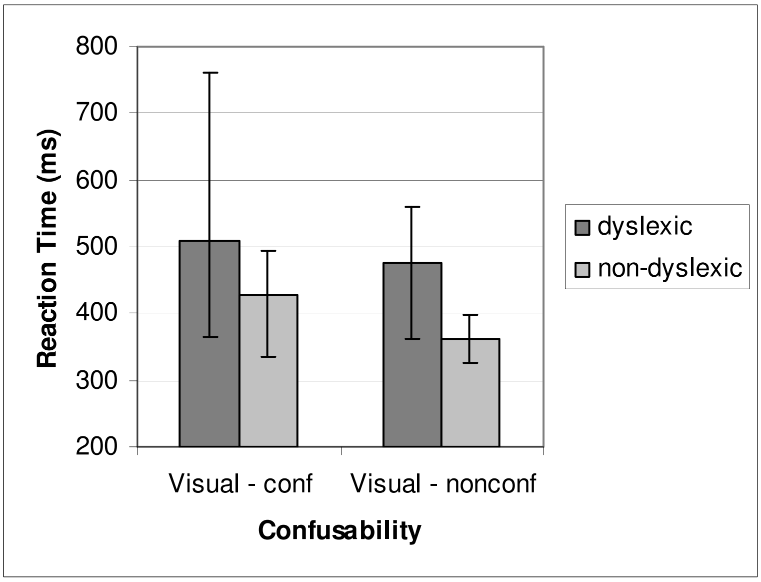


Figure 35: Group current processing time coefficients and 95 % confidence intervals in the confusable and non-confusable condition in the Visual Letter set.



The variable *Vocabulary* did not yield significant results in the Rime ($t = 1.12$, *n.s.*) or Onset ($t = 1.3$, *n.s.*) analyses. Vocabulary contributed significant variance in the Visual Letter set analysis ($t = 1.99$, $p < .05$), but again, its inclusion in the analysis did not change the pattern of results, suggesting that this variable cannot explain the variance contributed by dyslexic and non-dyslexic groups.

In sum, the findings across both *total* processing time and *current* processing time are very similar, suggesting that the ability to saccade to the next item and regress to re-process the target does not dramatically alter the pattern of target processing when a confusable item is available in preview. Our findings are also similar to the *Eye-Voice* span analysis with respect to the finding that the main influence of confusability and differences in reading group behaviour occurs in the Onset and Visual Letter set.

7.6.3 Errors

As in previous experiments, we obtained the sum of errors for each condition, which was then averaged across participants. Whereas previous experiments only indicated the total number of errors in each Letter set, with no indication of error types, the sound recording in this experiment allowed us to specify the type of errors made. Of primary interest was whether participants made errors based on rime, onset or visual substitutions. Two independent raters (one with no relation to this project) classified errors according to rime, onset or visual errors, in which the participant response was different from the target item, but had a similar rime or onset, or was visually similar to the target. Because the visual Letter set also contained items with similar rimes (e.g., *b* and *d*), we only included errors made in the relevant Letter set condition (e.g., the number of rime errors made in the Rime Letter set). This avoided bias in the number of errors made across different Letter sets if there was scope for one type of error to occur over another (e.g., a greater occurrence for rime errors over onset errors).

In total (including all errors: repetitions, no responses and incorrect responses in addition to our specific errors), the non-dyslexic group made 0.9% errors, whereas the dyslexic group made 1.6% errors. Table 23 demonstrates the average number of errors specific to rime, onset and visual errors for each group across conditions.

Table 23: Average error counts for each group across the factors *confusability* (confusable; non-confusable) in each Letter set.

	Rime -conf	Rime -nonconf	Onset -conf	Onset -nonconf	Vis -conf	Vis -nonconf
Non-dyslexic	2.52 (2.33)	1.52 (1.07)	2.36 (1.94)	1.26 (1.19)	3.52 (4.59)	0.26 (0.56)
Dyslexic	3.90 (2.86)	2.35 (1.59)	3.55 (4.55)	2.55 (3.57)	7.15 (4.33)	0.35 (0.67)
X^2	2.05	3.65	0.62	0.14	10.04**	0.11

Note: ** p <.01

A Kruskall-Wallis test demonstrated that the dyslexic group made significantly more errors in the visual condition when letters were paired for confusability, compared with the non-dyslexic group. There were no significant group differences in the other Letter set conditions, however, despite a trend for the dyslexic group to make more errors in each condition. A Wilcoxon test examined differences between confusable and non-confusable conditions for each Letter set, and yielded significant differences in each set, such that the confusable condition yielded more errors than the non-confusable condition (Rime: $Z = 2.76$, $p < .01$; Onset: $Z = 2.55$, $p < .05$; Visual: $Z = 5.09$, $p < .0001$).

7.7 Discussion

In Experiment 5, we used eyetracking methodology in order to investigate the processes underlying RAN (as representative of the low-level processes involved in reading fluency) with greater precision. The experimental design was similar to Experiment 4: letters were presented in confusable or non-confusable pairs in Rime, Onset and Visual Letter sets. Letter sets also comprised the same letter items as Experiment 4, apart from the visual items: following a pilot study, we decided to use visually reversible items. In this experiment, however, eyetracking allowed us to dissect the RAN, so that we could pinpoint (to the millisecond) how adjacent confusable items *preceding* and *succeeding* a target influence naming times, and how the results varied as a function of reading group.

An initial analysis investigated the effect of confusability on whole trial naming times: an average of the total naming times per trial (for each condition) was entered into the model in order that our results were comparable with previous experiments. In the Rime condition, the dyslexic group yielded longer latencies compared with the non-dyslexic group. Confusable conditions did not have a significant effect on latencies for either group, however. In the Onset and Visual conditions, on the other hand, a main effect of Confusability was found, such that the non-dyslexic reading group demonstrated longer latencies on trials in which visual and onset items were paired: the presence of visual or onset confusable letters slowed down non-dyslexic letter naming. Interactions emerged in both Letter sets (marginally so for the Onsets), such that the dyslexic group yielded relatively longer latencies on trials with adjacent-confusable letter pairs relative to non-confusable letter pairs compared with the non-dyslexic group.

A second analysis investigated the specific effect on target naming times of confusable items immediately preceding or succeeding the target. The *Eye-Voice* span measured the time from the initial fixation on the target to the voice onset of the articulatory response (the letter name). A similar, but not identical, pattern of results was found in the Eye-Voice span analysis. In the Rime Letter set, the dyslexic group yielded longer latencies than the non-dyslexic group, but again, no effect of confusable items was found, either when items preceded (the PREV analysis) or succeeded (the NEXT analysis) the target. In the Onset and Visual Letter sets, we did not find that the dyslexic group yielded generally longer latencies. However, target naming times in the non-dyslexic group were slower when the target was preceded by a confusable onset compared with when it was preceded by a non-confusable item.

We propose that this finding reflects a general difficulty in accessing phonological codes when a similar onset is already active in the articulatory loop. This proposal is supported by studies using tongue twisters to elucidate production processes, in which findings indicate that partially activated phonological representations affect the articulatory output (e.g., Goldrick & Blumstein, 2006). No such effect was found when a confusable onset succeeded the target, however, perhaps supporting Meyer et al.'s (1998) finding that when naming a serial list of items, phonological codes are activated before activation of the next item. (As we shall see, however, this explanation does not fit with the data obtained from the processing time analyses).

In the Visual Letter set, the non-dyslexic group's target naming times were not significantly influenced by visually confusable items in either position relative to the target. This suggests that non-dyslexic readers' *naming* times are resilient to active representations of visual competitors from either side of a target. Crucially, significant interactions again emerged in both Onset and Visual Letter sets demonstrating that the dyslexic group yielded longer target naming times when targets were preceded *or* succeeded by visually- or onset-confusable items.

A third set of analyses examined the processing time (reflected by how long the eyes spent processing the target letter item) and how these times varied as a function of confusable versus non-confusable items that succeeded the target item. Crucial to our findings was whether confusable items succeeding the target would influence target naming times before the eye saccaded to the next item, indicating preview effects (i.e. in the *current processing time* analysis). If we only found an effect of confusability in the *total processing time* analysis, however, this would suggest that processing time of the target is influenced by direct fixations on the next item, leading to regressions back to the target.

Our data demonstrated a very similar pattern of results across both *processing time* measures: consistent with findings from trial total times and the Eye-Voice span measure, the dyslexic group yielded longer processing time latencies on non-confusable trials in the Rime Letter set compared with the non-dyslexic group. However, the non-dyslexic group's target naming times did not vary as a function of confusability and no interaction emerged. In the Onset Letter set, on the other hand, an effect of Group was found: while the non-dyslexic group demonstrated longer target latencies on confusable compared with non-confusable trials, critically, the dyslexic group demonstrated an even greater discrepancy between confusable and non-confusable condition. A similar pattern of results was found in the Visual Letter set, but the Group x Confusability trend was not significant.

Findings from the processing time analyses therefore mostly concord with results from the Eye-Voice span analysis. For both reading groups, naming time and processing time lengthen as a function of their potential confusability with surrounding items. Two critical conclusions can be made from the findings from processing times, however. First, this data suggests that whilst visual information influences processing time for both reading groups, only confusable phonological *onset* information leads to longer processing times for dyslexic compared with non-dyslexic readers. This finding contrasts with results from the Eye-Voice span analysis, in which reading group performance was discriminated on confusable Visual as well as Onset items. Taken together, these findings suggest that dyslexic readers' processing time is impaired by phonological information. In addition, when the measure includes the production phase, however (Eye-Voice span analyses), retrieval of the orthographic code also incurs some penalty.

Second, both total and current processing time analyses yielded very similar results, suggesting that both reading groups' processing times are influenced by non-foveal information. That is, target processing latencies are influenced by the type of information presented in the parafovea, *before* the eye explicitly saccades to the next item. The current results therefore show evidence of parafoveal-on-foveal effects (Inhoff, Starr, & Shindler, 2000; Kennedy, 1998, 2000; Rayner, 1975; Underwood, Binns, & Walker, 2000) in the RAN. These findings have little bearing on the current debate in attention allocation during reading, however, owing to the different nature of the task.

In this study, we find that target processing and naming times are not only influenced by the phonological properties of the item succeeding the target, but also by the *visual* properties of that item. Our findings therefore stand in contrast with object-naming studies such as Meyer et al. (1998), in which participants are found not to begin processing the next object in the array until they have accessed phonological properties of the current (target) label. Our findings suggest that visual and phonological processing stages of the target therefore take place with reference to the upcoming item. The difference between our findings and Meyer's findings may reflect either the different processing requirements of orthographic stimuli over naming objects and/or the proximity of items in the array and its allowance of preview of the next item. Either way, these findings suggest a more parallel processing style across more than one item than has been previously demonstrated in the psycholinguistic and reading literature.

The current findings are of direct relevance in the interpretation of Experiments 1 and 3 of this thesis (Chapters 4 and 6): recall that in these experiments, continuous lists of letters in the RAN facilitated non-dyslexic readers' RTs compared with discrete lists, but the dyslexic group demonstrated comparable latencies across all formats. Our current findings suggest that non-dyslexic readers may show facilitated RTs for continuous lists because it enables simultaneous processing of the target in conjunction with visual and phonological processing of the upcoming item. From the current findings, we can also infer that much of this process is accomplished in the parafovea. Our findings from Experiments 1 and 3 with reference to the dyslexic group suggested that dyslexia may involve a more discrete processing style than is the case with non-dyslexic readers, in which targets are processed and named before processing upcoming items. This hypothesis concords with findings by Chace et al. (2005), for example, suggesting that dyslexic readers do not make use of parafoveal information when reading text. The present findings suggest that dyslexic readers *do* process parafoveal information when it is available, however, but with reference to the findings from Experiments 1 and 3, the additional information may provide more scope for confusion rather than being a facilitator of naming times.

The current pattern of results is also different, however, to our previous findings. Recall that in Experiment 4, both reading groups demonstrated longer RTs in response to confusable compared with non-confusable trials in Onset and Visual Letter sets. There was no Group x Confusability interaction, however. In the Rime Letter set on the other hand, an interaction did emerge, such that only the dyslexic group was slower in response to confusable items. Our current findings replicate the generally slower RTs in response to confusable compared with non-confusable items in Onset and Visual Letter sets, but also demonstrate that the dyslexic group show the longest latencies in confusable conditions. In contrast, confusable Rime items tend not to prolong naming times for either group. This pattern of results was found across four different measures, including the total time measure, which replicated the design of Experiment 4, suggesting that the current findings are robust. How then should we explain the differences in findings between Experiments 4 and 5?

Let us first consider the Onset and Visual Letter sets. In Experiment 5, the number of items presented in each RAN array was increased from 30 to 50 items, which mirrors the original number used by Denckla and Rudel (1976). In so doing, we increased the power of our analyses, which may have yielded the interaction observed. Recall also that we used different Visual items in this experiment (which, in our view, better represented this category), and this decision may also help to explain the presence of the interaction in the current experiment: in Experiment 4, it is probable that the ‘visually confusing’ items were simply not confusing enough. Explaining the presence of the Group x Confusability in Experiment 4 and its absence in Experiment 5 is more difficult, however. We propose that its occurrence in Experiment 4 may reflect the potential for error in a summed RT measure. Replication of the current results across several measures allows a firmer conclusion that the current results are robust and the interaction in Experiment 4 may be a spurious finding.

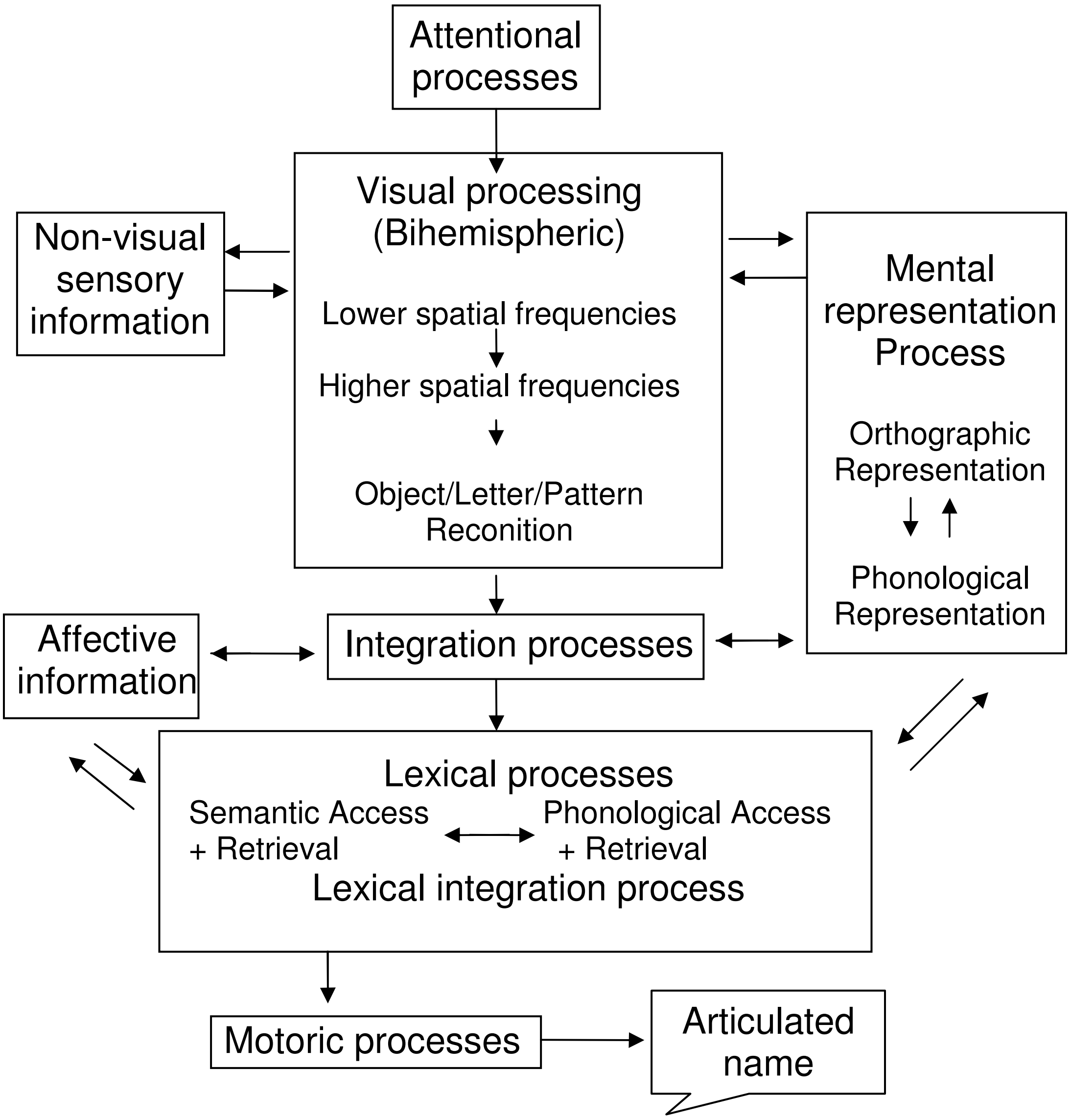
Finally, the error analysis in this experiment suggests that confusable trials in each Letter set yield significantly more errors than non-confusable trials. Although the dyslexic group showed a trend for making more errors overall, only one significant difference emerged in the number of errors between reading groups: dyslexic readers made significantly more errors in the visually confusable condition compared with the non-dyslexic group. This finding bolsters our finding of a non-phonological difficulty in the dyslexic group, and suggests that the dyslexic group may be prone to confusing items that are visually similar. This might lead to production of an incorrect name in addition to slow processing times. Note, however, that the increased number of errors in this condition for the dyslexic group did not artificially augment our RT data for the visually confusable condition: RT analyses were only conducted on correct responses to letter items.

7.7.1 Eyetracking and the study of reading fluency

The fine measurement allowed by eyetracking methodology implicates Experiment 5 as our best means in this thesis of identifying the processes involved in RAN (as a measure of the low-level processes of reading fluency) and how these processes, when aberrant, result in the naming-speed and fluency deficits characteristic of dyslexia. Specifically, it has enabled us to investigate the relationship between eye fixations and naming times in the context of dissecting the RAN into regions of particular interest (the precise effect of confusable items on target processing times). Given this wealth of data, we now turn to the different hypotheses of naming and fluency, and how the current findings can inform us as to which hypothesis best fits with our data.

Wolf and Bowers' (1999) outlined three main causal hypotheses of the influential processes in naming speed, as a measure of reading fluency, and which same processes are impaired in dyslexia (see Chapter 3). An established view held by many reading researchers is that phonological processes determine reading ability, and that phonological impairment causes reading impairment (see Snowling, 2000). As such, performance on the RAN is often considered a measure of how rapidly phonological codes can be retrieved from long term memory (Clarke et al., 2005; Snowling, 2000; Wagner et al., 1994). Wolf and Bowers specified the importance of the many processes underpinning naming, that represent a microcosm of the low-level factors underlying fluency, and outlined two (non-competitive) hypotheses. The first hypothesis identified visual processes as being critical in establishing rapid conversion of symbols into their corresponding codes. The second hypothesis emphasised a domain-general system, requiring rapid processing requirements at each stage in processing the stimulus leading to articulatory processes (see Figure 36 for a depiction of Wolf & Bowers' naming model and the different stages involved). The purpose of this thesis was not necessarily to distinguish between these two hypotheses, but to investigate the evidence for a non-phonological influence on naming speed and a non-phonological *deficit* in dyslexia.

Figure 36: Wolf and Bowers' (1999) naming speed model.



The manipulation of onset and rime information in this experiment and in Experiment 4 was done in order to test the potential of a phonological deficit in RAN and reading fluency, and to obtain an indication of which phonological segment influences task performance. As noted in Chapter 6, theorists have argued over whether awareness of larger phonological units (e.g., rime) or smaller units (e.g., phonemes) are better predictors of reading ability (e.g., Goswami & Bryant, 1990; Hulme et al., 2002). The results across all three levels of analysis (RAN total times, Eye-Voice span and processing time) suggest that taxing the ability to identify and name phonological onsets in RAN influenced naming times in the non-dyslexic group, and posed a particular problem (reflected by longer latencies) for the dyslexic group. Onset information for letter names in the RAN is short in comparison to the rime information. It often (but not always) corresponds to the phoneme represented by that letter (e.g., /k/ is the onset of the letter name for the letter ‘k’ - comprising the letters phonemic sound – and the rime /eI/). We propose that the dyslexic group’s apparent difficulty with onset information may reflect impairment with letter-sound knowledge. If true, dyslexic readers might also show impaired retrieval rates of grapheme-to-phoneme correspondences, which would disrupt fluent reading (Clarke et al., 2005; Wagner et al., 1993) However, it is also possible that this finding is specific to the current paradigm. When naming a letter, the range of possible onsets for letter names is broader than the range of rimes (e.g., the rime /I/ is very common in English names for letters of the alphabet). The constraints of the alphabet may make it harder to select an appropriate onset than an appropriate rime (because of the greater range of possible onset candidates compared with rime candidates).

Of critical importance to the main tenet of this thesis, however, was the consistent finding across all levels of analysis: *visual* information influenced processing times. The extent of this influence and its influence on separate groups varied according to the particular analysis: in the Eye-Voice span measure, for example, visual information had no significant impact on naming times for the non-dyslexic group, but it affected the dyslexics’ naming times. In the processing time measures, on the other hand, confusable visual information influenced both reading groups similarly. These findings suggest that visual information is an influential component when processing the item for all readers. Further, the effect of any visual confusion spills over into the production phase for dyslexic readers, but not non-dyslexic readers; indicated by the findings from the Eye-Voice span analysis.

With reference to our hypotheses, these results provide strong evidence of a non-phonological influence on naming speed in addition to a phonological influence on naming speed, in which visual information can also help determine naming times and implicate longer processing times for dyslexic readers. We cannot come to strong conclusions as to whether the effects in visual and phonological domains are directly related to naming speed (e.g., via impaired orthographic and phonological representations), or whether they are the result of cascaded influences from early attentional processes. Findings from the Eye-Voice span analyses, for example, consistently demonstrated that suppressing already-named information influenced target naming times. Further, processing upcoming items simultaneously with the target taxes the executive system, and it is possible that our findings in both sets of analyses reflect a primary attentional influence. An additional finding that perhaps supports this interpretation, and has been consistently found across all the experiments in this thesis, is that the dyslexic group demonstrate longer RTs than non-dyslexic readers irrespective of the experimental manipulation. In additional to the domain-specific manipulations reported in this and other experiments, therefore, the general group difference may reflect a domain-general attentional deficit or an impaired timing capacity, as suggested by Wolf and Bowers (1999) in their second hypothesis of naming speed deficits.

7.8 Chapter Summary

In this chapter, eyetracking methodology was used to investigate the effects of phonological and visual processing on fluency (measured in RAN naming times) in addition to the affects of attentional processes on naming times. In the production phase, we find that *visual* in addition to phonological onset information disproportionately influences dyslexic compared with non-dyslexic performance. Further, information provided in the previous and upcoming items influences target naming and processing times. We also find evidence that parafoveal information influences naming times for both dyslexic and non-dyslexic readers. In the next chapter, we investigate the root of a potential visual impairment in RAN and reading fluency, and its relationship to word reading accuracy.

CHAPTER 8

The contribution of visual-attention processes to fluency and word reading accuracy

8.0 Chapter Overview

Thus far, we have used experimental methods in order to investigate the evidence for non-phonological influences on reading fluency; reflected by performance latencies variations of the Rapid Automatised Naming (RAN) task. To this end, our experiments have been successful in identifying phonological *and* visual influences on naming speeds, and evidence of difficulty in both domains in the dyslexic reading groups. In this final experiment, we investigate which specific aspects of visual processing might influence naming speed, in addition to their relationship to other reading measures such as word reading accuracy. The study reported here is currently in press in the journal *Dyslexia: An International Journal of Research and Practice*, and a copy of this article is available in Appendix C.

8.1 Visual processing and reading

In the previous chapter, we obtained evidence to suggest that both phonological and visual domains influence naming speeds, supporting the multi-componential model of reading fluency put forward by Wolf and Bowers (1999). Our results cannot distinguish whether slower latencies in the dyslexic group reflect specific processing difficulty in these domains, or whether they are secondary to a primary attentional deficit, in which visual and phonological difficulties are symptomatic of a domain-general impairment. It is beyond the scope of this thesis to answer this question (see Chapter 9 for suggestions of further experiments with this aim in mind). However, models of reading that emphasise vision advocate a close relationship between visual and attentional processes (e.g., Stein & Walsh, 1997), and the study reported in this chapter aims to elucidate which visual processes relate to naming speed and measures of word reading. In this section, we review the current understanding of the visual substrates that influence reading ability.

8.1.1 The Magnocellular hypothesis revisited

In Wolf and Bowers' (1999) article, the authors propose that magnocellular dysfunction may comprise one potential cause of naming speed deficits in dyslexic readers. In the literature review of this thesis (Chapter 2), we reviewed the evidence for magnocellular deficits in dyslexic readers, and here we review the main points.

The Lateral Geniculate Nucleus (LGN) of the visual system is comprised of two pathways, which run in parallel, and to a large degree remain separate in their projection to the primary visual cortex (V1). Parvocells detect form and colour, which is not demonstrably impaired in dyslexia (e.g., Lovegrove et al., 1980). Magnocells detect transient movement information in the visual field (Galaburda & Livingstone, 1993). A number of studies proposed to tap magnocellular function demonstrate differences in performance between dyslexic and non-dyslexic groups. Sensitivity to dynamic visual stimuli (Cornelissen, Richardson, Mason, & Stein, 1995; Lovegrove et al., 1980; Lovegrove, Martin, & Slaghuis, 1986; Livingstone, Rosen, Drislane, & Galaburda, 1991; Mason, Cornelissen, Fowler & Stein, 1993), ability to detect coherent motion in random dot kinematograms (Cornelissen et al., 1995; Cornelissen, Hansen, Gilchrist, Cormack, Essex, & Franklish, 1998; Pammer & Wheatley, 2001), and ability to perceive global movement at short interstimulus intervals on a Ternus illusion task (Cestnick & Coltheart, 1999; Slaghuis, Twell & Kingston, 1996) are all impaired in dyslexic groups.

Stein and Walsh (1997) and Stein and Talcott (1999) proposed that magnocellular irregularity causes unstable fixations during reading, leading to inaccurate processing of orthographic information. Chase (1996) also proposed that inadequate processing of low-frequency visual information engendered by a magnocellular deficit might lead to slower activation of the appropriate grapheme in the child's lexicon. This view is supported by Bowers et al. (1994) and Bowers and Wolf (1993), who specify broader implications for reading ability. Bowers et al. (1994), for example, speculate that slow identification of individual letters leads to insensitivity to letter patterns in words (p. 203). Bowers and Wolf (1993) and Wolf and Bowers (1999) connect this position to naming speed and fluency: slow visual speed can contribute to reading difficulty in three ways:

> a) by impeding the appropriate amalgamation of connections between phonemes and orthographic patterns at subword and word levels of representation, b) by limiting the quality of orthographic codes in memory, and c) by increasing the amount of repeated practice needed to utilize codes before representations of adequate quality are achieved. (Wolf & Bowers, 1999; p. 426).

These deficits lead to an increased difficulty to automatise retrieval of lexicalised items, which is evident at the microlevel (in tasks such as RAN) as well as in fluent reading of text. Despite the intuitive appeal of a connection between magnocellular deficits and reading ability, a number of findings in the literature question the adequacy of a specific *magnocellular* deficit in explaining dyslexia. Findings relating magnocellular deficits and dyslexia have not been consistently replicated, nor are they found on multiple task comparisons (Evans, Drasdo, & Richards, 1994; Walther-Muller, 1995). Several studies also demonstrate an important role for visual attention but find no evidence of an additional magnocellular deficit (Iles, Walsh, & Richardson, 2000; Roach & Hogben, 2004; Steinman, Steinman, & Garzia, 1996; see Ramus (2003) and Skottun (2005) for reviews of the evidence relating to magnocellular deficits in dyslexia). Moreover, recent attempts to relate cued visual-search performance with more standard measures of magnocellular functioning (such as global dot motion; e.g. Cornelissen et al., 1998) failed to demonstrate a relationship between these tasks (Roach & Hogben, 2004). Whilst evidence of a visual deficit exists which may discriminate dyslexic and non-dyslexic reading groups, therefore, the evidence is mixed concerning the explanatory power of the magnocellular deficit hypothesis.

8.1.2 The dorsal deficit hypothesis

The magnocellular hypothesis of developmental dyslexia has therefore been substantially revised to include a stronger role for visual attention. From the primary cortex, two visual streams are known to project information to other cortical areas.

The dorsal stream (dominated by magno-inputs) projects to V2 and to V5 and the parietal cortex. Information carried by this stream is considered critical in the pre-attentive control of spatial selection. In contrast, the parvo-dominated ventral stream projects to areas V2, V3, V4 and the inferotemporal cortex, and operates a more detailed analysis of form, colour and texture (Vidyasagar, 1999). Recent research proposes that dyslexic visual deficits may be located in the dorsal stream (Pammer & Vidyasagar, 2005).

Vidyasagar (1999) and Pammer and Vidyasagar (2005) suggest that different processing styles exhibited by dorsal and ventral visual pathways reduce the computational load on the visual system that might arise if both pathways operated simultaneously on the same visual input features. The dorsal stream acts as an *attentional spotlight*, guiding visual attention to salient components of the visual stimulus. A decision is made concerning regions of interest which is followed by more detailed (ventral) processing of that region (Pammer & Vidyasagar, 2005). In reading, the dorsal stream allocates attention to appropriate areas of text, providing sufficient feedback to the ventral stream to allow fine-grained analysis of letters (Pammer & Vidyasagar, 2005). Empirical findings that dorsal functioning is critical in the pre-lexical stages of word processing support this account (Mayall, Humphreys, Mechelli, Olson, & Price, 2001). A dorsal stream *deficit* might therefore impede smooth attentional focus on orthographic items, disrupting the visual discrimination of letters that is accomplished by the ventral stream (Pammer & Vidyasagar, 2005). It should be noted here that Pammer and Vidyasagar's (2005) work was influenced by Treisman's (1988) Feature Integration Theory, in which the dorsal pathway is thought to implement a parallel search mechanism, which is subsequently fed to the ventral stream (extending to V2, V3, V4 and the inferotemporal cortex, ITp). The ventral stream then implements a serial temporal search of each item to determine feature integration.

8.1.3 The contribution of dorsal functioning to reading

Late stages of dorsal stream functioning involve the parietal cortex, which serves to deploy and control visual attention across different regions of the visual field (e.g.

Arguin, Joanette, & Cavanagh, 1993; Corbetta, Miezin, Shulman, & Petersen, 1993, 1995). The *conjunction* search task, in which a target stimulus differs from distracter items in two or more ways, is a means of testing parietal cortex functioning. Typically, reaction times on conjunction tasks increase linearly with increased set sizes, suggesting that each stimulus is processed in turn, requiring a shift in visual attention (e.g. Ashbridge, Walsh, & Cowey, 1997). When compared on conjunction tasks, child and adult groups of dyslexic and average readers show reduced accuracy levels (Buchholz & McKone, 2004; Casco & Prunetti, 1996; Iles et al., 2000; Vidyasagar & Pammer, 1999). Low accuracy levels reflect a reduced ability in the parietal cortex to shift attention across the visual field (Buchholz and McKone, 2004). However, in tasks believed to be mediated by the ventral stream, requiring attention to fine spatial detail, such as visual acuity, good and poor readers perform equally well (Buchholz & McKone, 2004; Pammer & Wheatley, 2001).

The precise impact of a dorsal stream deficit on reading remains elusive, however. Pammer, Lavis and Cornelissen (2004a) investigated whether dorsal stream functioning influences reading ability via letter-position encoding. Letter-position encoding refers to the readers' sensitivity to the relative locations of orthographic items within a string; less skilled readers are more inaccurate in judging item position compared with highly skilled readers (e.g. Mason, 1980). One measure of letter-position encoding is the *symbols task*, in which symbol strings are briefly presented to the participant; the participant memorises each item and their position in the string and then selects the correct string from a forced choice of two alternatives. Using letter-like symbols (with no resemblance to letters of the Roman alphabet) reduces lexical influences, yielding a measure of how well the relative positions of items are visually encoded. Children with dyslexia give fewer correct responses in this task than non-dyslexic readers (Pammer, Lavis, Hansen, & Cornelissen, 2004b). Furthermore, performance on the task significantly predicts word recognition ability in adults (Pammer, Lavis, Cooper, Hansen, & Cornelissen, 2005).

Previous research correlated performance on the symbols task with a measure of dorsal functioning – Frequency Doubling Technology (FDT), which involves threshold measurement for pattern detection – in order to investigate the relationship between dorsal functioning and letter-position-encoding mechanisms (Pammer et al., 2004a). Pammer et al. found no relationship between these tasks, but both measures were related to reading. Pammer et al. suggest a division of labour for spatial processing in reading, such that dorsal functioning operates a coarse, peripheral analysis of text independently of the detailed, spatial analysis provided by ventral processes that underpins letter-position encoding.

Experiment 6

Visual processing and reading ability

8.2 Rationale and predictions

Experiment 6 aims to investigate the relationship between visual processing and components of reading ability, such as naming speed and word naming accuracy. The final experiment of this thesis therefore aims to elucidate the visual processes underpinning fluency, but also to examine its role in a more general reading context, involving word reading. In order to accomplish this, we present participants with three visual tasks (outlined in the following section) proposed to tax dorsal stream functioning. We argue that in two of these tasks (symbols and visual-search), good performance requires efficient pre-attentive selection by the dorsal stream in order for fine grained analysis of the stimuli to be accomplished (e.g., Pammer & Vidyasagar, 2005). If such cooperation between the dorsal and ventral streams underpins reading ability to some extent, we expect to find group differences on these measures. Further, we expect that performance on these tasks will be related to measures of reading ability. Of primary interest for our purposes in this thesis is to investigate the relationship between these tasks and RAN, as an index of fluency. We were also interested, however, in whether performance on the visual tasks would predict other measures of literacy, such as word naming accuracy. Finally, if reading ability can also be determined by the magno-dominated input to the dorsal stream, we expect group differences on the third (Ternus) task. In the following section, we introduce the three visual tasks used in this study.

8.3 The visual tasks

Letter-position encoding ability was measured using the symbols task, which has previously demonstrated discrepancies between dyslexic and non-dyslexic groups (Pammer et al., 2004b). We measured visual attention using a cued visual-search attention task involving exogenous cueing of a target presented amongst identical distracters (see Roach & Hogben, 2004). Exogenous cueing involves a peripheral cue that precedes a target by a short delay; provoking an involuntary shift in attention towards the location of the subsequent target (e.g. Facoetti et al., 2003; Warner, Juola, & Koshino, 1990). Exogenous cueing facilitates non-dyslexic readers' accuracy in predicting target location, but yields no such benefit for dyslexic readers (e.g. Facoetti, Turatto, Lorusso, & Mascetti, 2001; Roach & Hogben, 2004). In our version of the cued visual-search task, participants had to identify the target's tilt direction as well as its location. The attention allocated to the target region by dorsal processes would then allow rapid target selection in the ventral stream, given the unique tilt property of the target amongst vertical distracters (Vidyasagar, 1999).

A third 'Ternus' task involved motion perception. In early studies, Lovegrove used sine wave gratings interspersed by a blank interstimulus interval (ISI) and measured participants' ability to perceive the blank ISI (e.g. Martin & Lovegrove, 1988; Slaghuis & Lovegrove, 1984). Failure to perceive the blank ISI was originally interpreted as *visual persistence* of the first item at the time the second was displayed: when Stimulus 2 was presented, the magnocellular system failed to override form (parvo) information of Stimulus 1 (Breitmeyer & Ganz, 1975).

Tasks based on this principle have yielded a substantial body of evidence that poor readers have longer-lasting visual persistence than good readers: they require longer ISIs than good readers in order to perceive group movement (e.g. Cestnick & Coltheart, 1999; Martin & Lovegrove, 1984, 1988; Slaghuis & Lovegrove, 1984, 1985, 1986a, b; Slaghuis et al., 1996; Winters et al., 1989). One such task is the Ternus task (Ternus, 1938), which comprises three horizontally aligned squares presented briefly (frame 1), then presented again moved one imaginary square's breadth to the right (frame 2). The frames are alternated a number of times. Two types of motion detection ensue, depending on the length of interstimulus intervals (ISIs) between frames: short ISIs result in "element" (or single) movement perception, in which the leftmost square is perceived to jump to the right hand side from frame 1 to frame 2, whereas longer ISIs (~50 ms and above) result in "global" (or group) movement perception, in which all three squares move as a group to the right. Breitmeyer & Ritter (1986) hypothesised that the onset of group movement perception marks the point at which magnocellular functioning terminates visual persistence by inhibiting the parvocellular system. However, Kramer and Rudd (1999) demonstrated that element movement can be perceived in the absence of visual persistence. Skottun (2001) proposed that a single mechanism may govern both perceptual element and group movement perception, but they reflect different levels of processing: whilst element movement reflects subcortical processes, group movement is located at or beyond the primary visual cortex (see Skottun, 2001).

8.4 Method

8.4.1 Participants

The current experiment was conducted with the same reading population for both dyslexic and non-dyslexic groups as those participating in Experiment 3 of this thesis. (See Chapter 6 for details concerning group differences on cognitive and literacy tests).

8.4.2 Materials

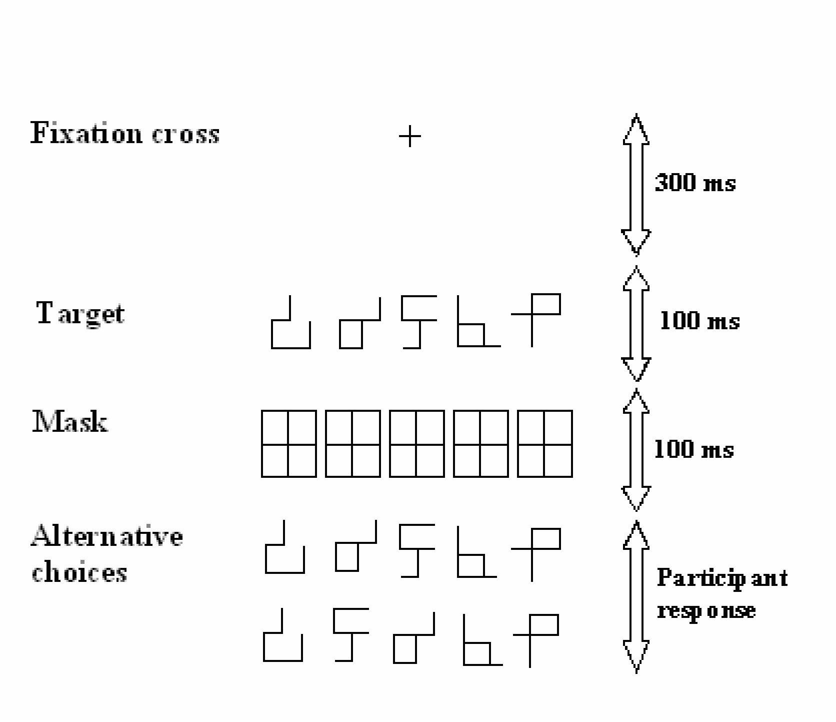
All tests were presented using E-prime version 2 software (Schneider, Eschman & Zuccolotto, 2002) on a Windows PC and were displayed on an Iiyama HM703UT VisionMaster Pro 413 RM monitor with a resolution of 1024 x 768 pixels. Participants sat at a distance of approximately 60 cm from the screen.

8.4.3 Design and Procedure

8.4.3.1 The Symbols Task

A symbol string comprised five adjacent symbols from a selection of 20, yielding a vertical angle of 2.5 ° and an angle of 5° horizontally. Each symbol comprised a similar number of vertical and horizontal lines to alphabetic letters, but with minimal similarity to actual letters. This design is similar to Pammer et al. (2004a), but whereas these authors used white symbols on grey, we presented items in black type on an off-white background to mimic normal contrast characteristics of reading. Target strings were presented for 100ms, followed by a mask for 100ms. Two symbol strings were next presented one above the other (see Figure 37), yielding a forced choice decision of which they had seen. Within-string symbol swaps comprised one third 2nd and 3rd swaps, one third 3rd and 4th swaps, and one third 2nd and 4th swaps in random order, comprising 60 trials in total. 10 practice items preceded the experimental session. The design therefore yielded a single variable Group (dyslexic; non-dyslexic) on the symbols task.

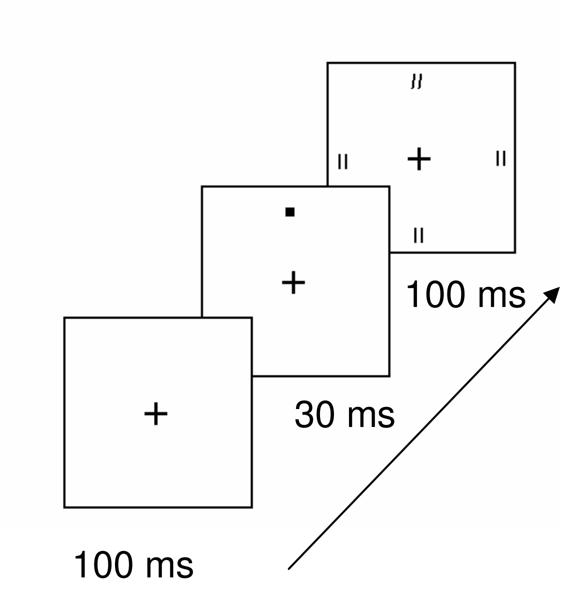
Figure 37: Example trial of the Symbols task.



8.4.3.2 The Visual-Search Task

Target and distracter items were presented for 100ms per trial in a circular display surrounding a central fixation cross at a visual angle of 5° (see Figure 37). A target comprised off-vertical items (tilting 10° either to the right, e.g. // or the left, e.g. \\) similar to the grating patches used by Roach and Hogben (2004). Distracters were vertical items (||). Targets and distracters were controlled for size (font 18) and were black on an off-white background. Each stimulus subtended a visual angle of 0.5°, and one target was presented per trial. Participants saw a fixation cross for 100ms. On half the trials at each set size, this was followed by a 30ms cue in the exact position of the subsequent target item; on the other half there was no cue. Between trials, on-screen instructions prompted participants to indicate the direction of tilt by pressing either of two buttons. Stimulus sets (including target and distracters) were blocked according to stimulus set size (2, 4, 8, and 16), yielding a total of 160 trials. Eight practice items (2 of each set-size) were preceded the experimental session. The visual-search task therefore yielded a 2 (Group: dyslexic; non-dyslexic) x 4 (stimulus set size: 2, 4, 8, and 16) design.

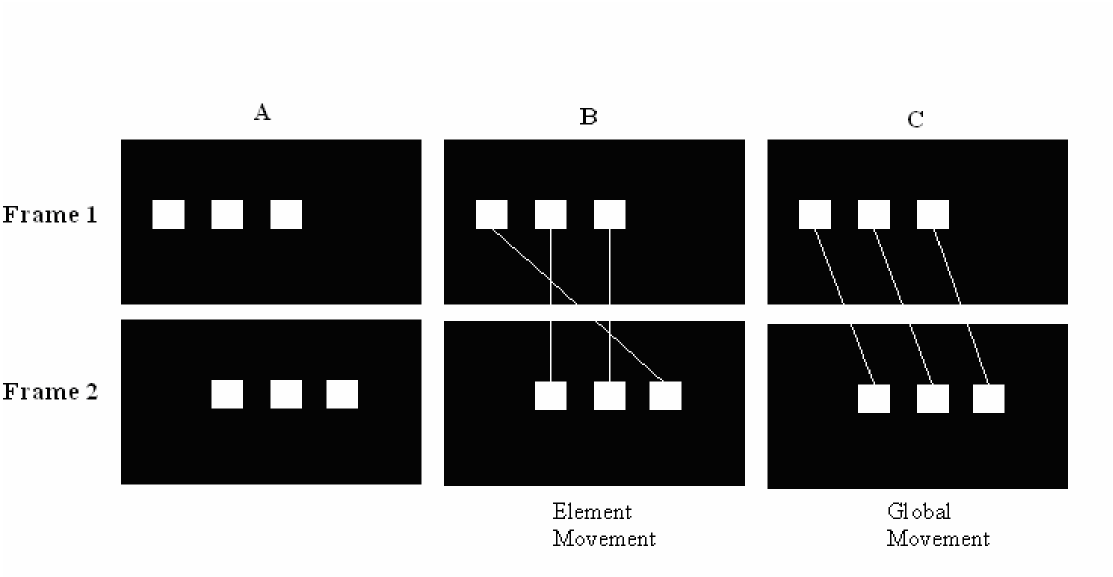
Figure 38: Example trial of the Visual-search task in the cued condition.



8.4.3.3 The Ternus Task

Three white squares were presented on a black background. The visual angle was identical for the side lengths and the distance between each square (3°). One trial consisted of 8 alternations of two display frames. The first display frame presented 3 squares in a fixed screen position; in the second, the leftmost square was transferred to the rightmost position, whilst the position of the other two squares remained constant. Figure 39 demonstrates the different ways of perceiving movement of squares in the Ternus task: element movement is perceived at short ISIs (column B), whilst global movement is perceived at longer ISIs (column C). The duration of each display frame was 55ms, with varying ISI length between the display frames per trial: 8, 16, 24, 32, 40, 48, 56, 64, 72 and 80 ms (8ms steps as opposed to 8.3ms steps used in Cestnick and Coltheart (1999); these figures also take into account the screen refresh rate). ISI length was randomised across the experiment. There were 10 trials in each ISI condition, yielding a total of 100 trials per participant. The experiment was self-paced; participants were presented with a forced choice decision of "global" or "element" movement perception, which they indicated by pressing either of two buttons on the button box. 10 practice trials (one of each ISI length) preceded the experimental session.

Figure 39: Example Element (B) and Global (C) perceptions of movement on the Ternus task.



8.5 Results

We measured frequency of correct responses for both the symbol-string and visual-search tasks, including individual mean values for each set size and for the cued and uncued conditions, and frequency of reported *global movement* perception for the Ternus task (means and standard deviations are reported in Table 22).

8.5.1 Group differences

To establish whether the visual tasks could distinguish between groups of dyslexic and non-dyslexic readers, we first analysed group differences.

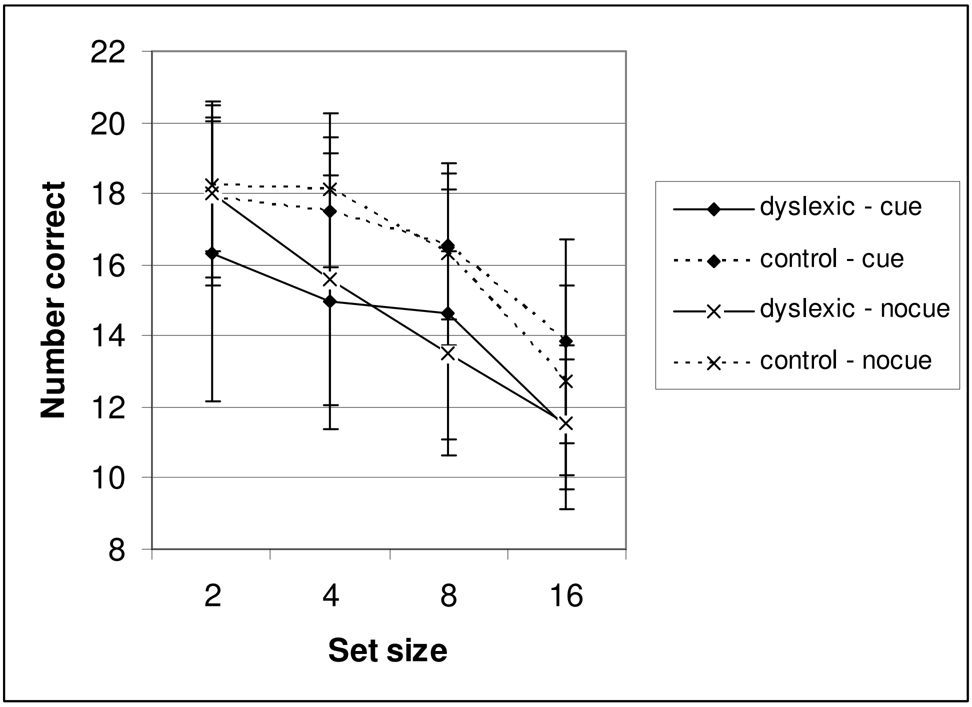
A between-participants one-way ANOVA (dyslexic vs. non-dyslexic) on the number of correct responses in the symbols task demonstrated an effect of Group (F (1, 36) = 5.42, $p < .05$). Table 24 shows that there were more correct responses in the control group than in the dyslexic group.

Table 24: Reading group differences on the Symbols, Visual-search (across all set-sizes) and Ternus tasks (across all ISIs); standard deviations in parentheses.

	Group							
Task	Dyslexic			Non-dyslexic			N trials	Cohen's *d*
	Mean (SD)	%	Range	Mean SD)	%	Range		
Symbols: N correct	34.88 (7.26)	58	26.21-45.66	41.81 (7.74)	81	29.67 -59.84	60	0.92
Visual-search (cue): N correct	13.95 (2.55)	35	8.75-17.50	16.42 (1.77)	41	13.51 -19.67	80	1.12
Visual-search (no cue): N correct	14.50 (1.94)	36	10.58-17.53	16.39 (1.73)	42	12.75 -18.75	80	1.02
Ternus: N perceived global movement	48.40 (12.10)	48	27.-68.	50.95 (8.98)	51	39.56 -76.61	100	0.23

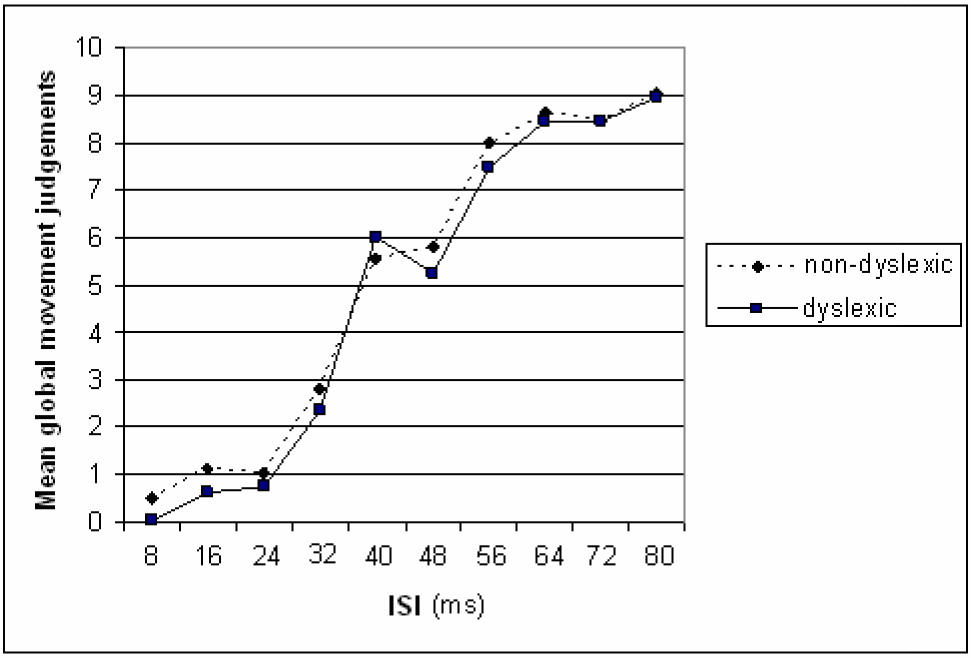
A repeated measures 2 x 2 x 4 ANOVA with the levels Group (dyslexic vs. non-dyslexic), Cue (cue vs. no cue) and stimulus Set size (2, 4, 8, 16 items) on the number of correct responses in the visual-search task yielded a main effect of Group (F (1, 36) = 9.83, $p < .01$): Table 24 shows that dyslexic participants gave fewer correct responses than non-dyslexic participants. There was also a main effect of Set size (F (3, 108) = 66.03, $p < .001$); performance decreased as a function of Set size (all differences significant at $p < .01$) (see Figure 40). However, there was no main effect of Cue ($F = .24$, $p = .63$) nor a Group x Cue ($F = .89$, $p = .35$) or Group x Set size interaction ($F = 1.77$, $p = .16$). There was however a significant Cue x Set size interaction (F (3, 108) = 3.28, $p < .05$); Figure 40 suggests that the presence of a cue was more likely to induce a correct response for smaller rather than larger set sizes.

Figure 40: Mean number of correct responses as a function of set size across cued and uncued condition (standard deviations represented by error bars).



We analysed the number of group-movement responses in the Ternus task using a 2 x 10 ANOVA with the levels Group (dyslexic vs. control) and ISI (8, 16, 24, 32, 40, 48, 56, 64, 72, 80 ms). There was no main effect of Group (*F* = .644, *p* = .428) (see Figure 41), Hence there was no greater propensity for non-dyslexic participants to begin detecting group movement at shorter ISIs than dyslexic participants. There was however a main effect of ISI (*F* (9, 324) = 194.76, *p* < .001): overall, participants reported higher incidence of group movement at longer ISIs. There was no interaction between group and ISI (*F* = .40, *p* = .93). The standard deviations in Table 24 suggest, however, that there was greater variability in the dyslexic group compared with the non-dyslexic group on the Ternus task. Cohen's d analysis measuring individual dyslexic participants against the non-dyslexic mean revealed that 3 members of the dyslexic group yielded a Cohen's d value of above 1: performing one standard deviation below the non-dyslexic mean. Despite a lack of group difference, therefore, these findings indicate that a small number of the dyslexic group experienced significant difficulty on the task.

Figure 41: Mean global movement judgements as a function of ISI across reading groups.



8.5.2 Regression

We next investigated the relationships between the visual tasks, and between these tasks and literacy. Literacy measures, including the RAN, exception and non-word naming scores (in addition to the other cognitive and literacy tests) were obtained in the experimental session described in Experiment 3 (Chapter 6), which comprised a separate experimental session to the visual tasks. For every participant, RAN scores comprised their average latency across each trial in the experiment. Exception and non-word scores comprised a total number of errors per participant.

Because our goal was to investigate whether the dorsal stream mediates skills such as letter-position encoding and component reading skills, only responses for the cued condition of the visual-search task, in which an involuntary shift in attention indicative of dorsal stream processing occurred (Vidyasagar, 1999), were entered into the analysis. Non-word reading, exception word reading and Rapid Automatised Naming demonstrated positively skewed distributions and were corrected for normality before analysis using a log transfer. Table 25 reports results of a correlation analysis including the three visual tasks and the four component reading measures. Performance on the visual-search and the symbols tasks are significantly correlated. Furthermore, both visual-search and symbols performance correlate with non-word reading and Rapid Automatised Naming speed.

Table 25: Correlation matrix of all variables.

	Symbols	Visual-Search	Ternus	Non-words	Exc. words	RAN
Symbols	-					
Visual-Search	.296*	-				
Ternus	.050	.003	-			
Non-words	-.291*	-.416**	-.015	-		
Exc.-words	-.120	-.134	.043	.507**	-	
RAN	-.282*	-.275*	.031	.477**	.376**	
Spelling	.213	.102	-.146	-.654**	-.463**	-.581**

Note: * $p < .05$; **$p < .01$; (95% confidence intervals for significant correlations).

A series of simultaneous multiple linear analyses determined the extent to which the three visual tests predicted different reading component measures (see Table 26). Predictors in each analysis comprised the number of correct responses for the visual-search task (cued condition); the number of correct responses for the symbols tasks; and the reported number of "global" movements reported in the Ternus task. Dependent variables on separate analyses comprised the number of errors in phonological decoding (non-word naming); whole word recognition (exception word naming); reaction-time (RT) for rapid automatised naming (RAN); and standardised spelling scores (WRAT-3).

Table 26: Symbols task performance regressed on phonological decoding, exception word recognition, rapid automatised naming and spelling.

Variable	*B*	*SE B*	*B*	R^2	*F*
Phon. Decoding					
Constant	2.12	.58		.45	2.90*
Symbols	- .01	.01	-.18		
Visual-search	- .07	.03	-.36*		
Ternus	- .00	.07	-.01		
Exc. word naming				.03	0.31
Constant	.74	.49			
Symbols	-.00	.01	-.09		
Visual-search	-.02	.03	-.11		
Ternus	-.02	.05	.05		
RAN				.35	1.57
Constant	4.39	.143			
Symbols	-.00	.00	-.22		
Visual-search	-.01	.01	-.21		
Ternus	.00	.02	.04		
Spelling				.07	0.46
Constant	97.06	22.73			
Symbols	.42	.35	.21		
Visual-search	.27	1.18	.04		
Ternus	-.39	2.52	-.16		

Note: * $p < .05$

The analyses showed that visual-search task performance contributed significant unique variance to phonological decoding ($t = 2.26$, $p < .05$), but none of the tasks contributed significant unique variance to exception word reading, rapid automatised naming or spelling.

8.6 Discussion

8.6.1 Reading group differences on visual tasks

We measured the ability of visual processes to discriminate reading groups in addition to their value in predicting reading measures. Our results suggest that there are robust differences in visual processing between dyslexic and non-dyslexic readers, even in these high-functioning samples, and that some of these differences are associated with specific impairments on reading component measures.

The symbols task measured performance in letter-position encoding, whilst excluding lexical bias. Consistent with previous results, dyslexic readers made fewer correct responses than non-dyslexic readers, suggesting impaired letter-position encoding (Pammer et al., 2004b).

The visual-search task measured visual attention; in the cued conditions, it required efficient dorsal stream functioning (to orient attention to the target position) as well as ventral processing (to discriminate the target orientation). Overall, dyslexic readers made fewer correct responses than non-dyslexic readers, suggesting difficulty in rapid identification of the target and its orientation. Furthermore, performance declined for both groups as a function of set size, but cued conditions did not facilitate performance relative to uncued conditions for either group. Despite the similarity of our design to other studies' (Baldassi & Burr, 2000; Roach and Hogben, 2004), the non-dyslexic readers in our study did not replicate previous findings of enhanced performance when a cue preceded the target. Although otherwise identical, the cue used in this study yielded a smaller visual angle than in previous studies (approximately 10° compared with 25°), allowing for the possibility that its exogenous cueing potential was reduced.

One explanation for these findings is that participants' performance may reflect other cognitive processes in addition to impaired dorsal processes in this version of the visual-search task. The rapid visual processing demands in addition to task complexity (combining a visual search with an orientation decision) may tax dyslexic readers' domain-general processing speed capacity (see Wolf & Bowers, 1999, for a review); a possibility we discuss below.

Although cueing did not increase accuracy rates for either group, the significant Cue x Set size interaction, suggests that both reading groups were sensitive to the presence of the cue. For both groups, a cue facilitated tilt-orientation judgement when preceding a small number of distracters, but adversely affected performance when preceding a large number of distracters. One possibility is that in this type of visual-search task, involving identification of a tilted target in the presence of vertical distracters, participants employ different search strategies for small as opposed to large set sizes (Pammer, personal communication). In our study, the short presentation time meant that whilst serial search could be employed for smaller set sizes, in larger set sizes, the time limit coupled with the closer spatial juxtaposition of the target with distracters may have prompted a compare-and-contrast search mechanism. When a serial search strategy was employed, the cue may have oriented participants' attention to the target's location, thus facilitating performance accuracy. Our results suggest, however, that in larger set sizes, the cue information was irrelevant, and at worst interfered with the strategy that was used.

Consistent with previous findings, both reading groups in our Ternus task demonstrated a similar pattern of increased *global* movement judgements in response to longer ISIs (e.g. Cestnick & Coltheart, 1999; Slaghuis et al., 1996). In contrast to Cestnick and Coltheart (1999), however, dyslexic readers did not report fewer global judgements overall relative to non-dyslexic readers. Considering the similarity of our Ternus design to that used by Cestnick and Coltheart, this difference in our results is difficult to interpret. However, Cestnick and Coltheart tested children, rather than adults: it may be possible that the high functioning adults used in the present sample have compensated somewhat for difficulty on the Ternus. Another explanation for the absence of magnocellular deficits often found in dyslexic groups is that the deficit is so mild in these groups that difficulty only arises when magnocellular input is required for the direction of sequential attention (Vidyasagar, 1999). Extending this explanation to the current study, our results suggest that in our high functioning sample, a visual deficit was found only when the task required application of a visual search mechanism. The Ternus did not involve such a mechanism and did not therefore discriminate groups of dyslexic and non-dyslexic readers. It should be noted, however, that three members of the dyslexic group did show some impairment on this task, perhaps indicating a residual difficulty that might have been experienced by a greater number of the group had they been tested during childhood.

In summary, analyses of group differences show that the adult dyslexic group are impaired relative to non-dyslexic controls on two of the three visual tasks. The symbols task indicates a deficit in letter-position encoding (e.g. Pammer et al., 2004b). In the visual-search task, cued targets did not facilitate accuracy in the non-dyslexic group, rendering interpretation of the overall dyslexic deficit more difficult. The dyslexic deficit may best be interpreted as a cognitive processing-speed or visuo-spatial working memory impairment, but dorsal processes may mediate the sensitivity to cued items demonstrated by both groups. The Ternus task did not discriminate reading groups.

8.6.2 Contribution of visual processing to reading component measures

We next investigated whether the visual tasks map onto components of reading. Performance on symbols and visual-search tasks correlated with Rapid Automatised Naming and non-word reading, reflecting phonological ability and naming speed respectively. Previous studies indicate a relationship between visual attention (motion sensitivity) and exception word reading (Talcott et al., 2000), but none of our visual tasks contributed significant variance to this reading component. Our finding almost certainly reflects the adult, high-functioning reading population investigated in this study, resulting in possible floor effects: low error counts were found in the exception word task for both groups.

Performance on both the symbols and visual-search tasks also correlated with RAN, despite the fact they did not contribute independent variance to this measure. One potentially important commonality between the two visual tasks and RAN is their emphasis on fast visual processing. Both visual tasks involve short presentation times, requiring rapid visual processing for good performance, suggesting that the rapid visual processing required for successful performance in these tasks is also an important determiner of naming speed. This finding is relevant to the current controversy surrounding the cause of rapid naming deficits in dyslexia, specifically whether slower naming in dyslexic readers reflects impaired covert phonological deficits (Clarke, Hulme & Snowling, 2005) or has an independent root cause, linked to lower level visuo-attentional and/or timing processes (Wolf & Bowers, 1999). Our results suggest that the ability to rapidly process visual information predicts the speed with which letter items can be named, suggesting that rapid visual processing is a critical factor in naming speed ability.

Both the visual-search and symbols tasks contributed significant variance to non-word reading, suggesting a common causal link between visual attention, letter-position encoding and phonological decoding: each task reflects a successively “higher” stage of processing, ranging from perceptual to cognitive domains. However, our results showed that visual attention predicts phonological decoding independently of letter-position encoding. Thus the evidence suggests that visual attention and letter-position encoding share a common mechanism, but visual attention contributed separately to reading (Pammer et al., 2004a). In this study, however, letter-position encoding did not contribute independent variance to decoding when performance on the visual attention task was controlled, suggesting that the relationship between letter-position encoding and decoding is in part mediated by visual-attention mechanisms. Given the close relationship between vision and attention during the early, perceptual stages (e.g., Vidyasagar, 2004), however, we also cannot rule out the possibility that deficits observed at this visual stage reflect the cascaded influence of an attention deficit.

There was no correlation between performance on the Ternus task and any of the component reading measures, in contrast to previous findings (e.g. Cestnick & Coltheart, 1999; Cornelissen et al., 1998). Taken together with the absence of reading group differences, one interpretation is that for at least these high functioning adults, a visual task that did not include a search mechanism, and did not implicate dorsal and ventral processes, did not distinguish dyslexic readers’ performance from non-dyslexic readers.

Further analyses regressed performance on the visual-search, symbols and Ternus task against non-word naming, exception word naming and RAN. Performance on the visual-search task contributed unique variance to non-word naming performance, but no other variables contributed significant unique variance to reading ability. Our results therefore show a relationship between visual attention and phonological decoding. Cestnick and Coltheart (1999) proposed two hypotheses of the way in which visual magnocellular function influences non-word reading. First, the attentional shift required for eye movements may affect the serial processing of letters required for non-word reading. Alternatively, magno cells responsible for processing auditory information might influence phonemic decoding proficiency. Our findings suggest that higher level visual attention processes, potentially controlled by dorsal functioning, affect phonological decoding ability.

Our findings are consistent with the SERIOL reading model (Whitney & Cornelissen, 2005), in which processing letter strings involves making graphemic and phonemic connections between letter items serially. According to this model, each letter receives peak acuity levels across the letter string in turn, firing in a strict left-to-right sequence, and accurate representations of grapheme-to-phoneme correspondence can only be obtained when acuity levels operate in this manner. We suggest that if the dorsal stream is ineffective in guiding attention serially over the letter string, then attention is more dispersed and two or more letter items may be associated with a single phonological label. As a result, phonological codes are ill defined, which is problematic when trying to decode novel or non-words. Furthermore, serial deployment of attention may be particularly pertinent to non-word reading, since whole-word lexical strategies are not available.

8.7 Chapter summary

With reference to the concerns of this thesis, the critical finding is that performance on both symbols and visual-search tasks are significantly related to RAN latencies. We suggest that a common feature of these visual tasks is the interplay between pre-attentive search mechanisms and fine discrimination of visual detail, and the current findings suggest that a similar mechanism may underpin RAN speeds. Low-level visual processes may therefore have an important influential role in determining reading fluency. The relationship between visual processing and RAN is discussed further in Chapter 9, with reference also to findings from previous experiments reported in this thesis. In a broader context, findings from Experiment 6 also suggest that similar visual processes are also related to aspects of reading such as non-word decoding.

CHAPTER 9

Summary and Conclusions

9.1 The aim of this thesis

Rapid Automatised Naming (RAN) measures have been used to identify children with dyslexia who are slower, or more disfluent, when reading (e.g., Denckla & Rudel, 1976). RAN comprises a 'microcosm' of the low-level processes involved in reading fluency, and a body of literature suggests that it contributes unique variance to reading ability, beyond that accounted for by phonological awareness (e.g., Cutting, Carlisle, & Denckla, 1998). Wolf and Bowers (1999) propose that performance on the RAN represents the complexity of all the component processes brought to bear for reading. Under this account, attentional and visual domains have a primary influence on reading fluency, in addition to the influence of phonological processing. Other researchers (e.g., Clarke et al., 2005), however, propose a primary influential role for *only* phonological processing.

The aim of this thesis was to investigate the evidence for *extra*-phonological influences on RAN RTs in general, and to assess whether they could explain the naming speed deficit in dyslexia. In order to accomplish this, we compared dyslexic and non-dyslexic young adult readers on a series of experiments designed to isolate or tax the phonological and non-phonological component processes involved in RAN.

9.2 Summary of the main findings

Previous research demonstrated that *continuous* RAN formats, in which letters are presented in a grid format, are better predictors of reading than *discrete* formats, involving individual letter presentation (e.g., Bowers & Swanson, 1991). In the absence of any further research elucidating the nature of this relationship, our starting point for the thesis involved asking which behaviours underlie continuous and discrete RAN tasks and which of these behaviours pose a difficulty for dyslexic readers. Experiment 1 therefore compared dyslexic and non-dyslexic reading groups on *continuous* and *discrete* versions of RAN, in addition to a novel *discrete-matrix* condition, which isolated the effects of eye movements on RAN performance. Our results indicated that non-dyslexic readers showed facilitated naming times in the continuous RAN formats, suggesting an advantage for processing multiple items in the RAN. In contrast, the dyslexic group showed no significant difference in processing times across the different presentation formats.

Experiment 1 demonstrated that the ability to sequence multiple items in the RAN influences naming speeds, suggesting that *extra*-phonological processes are at work in RAN (Wolf & Bowers, 1999). The absence of a facilitation effect in the continuous format for the dyslexic group might indicate a visual difficulty in allocating attention to more than one item simultaneously (Valdois, Bosse, & Tainturier, 2004, 2006), a parafoveal processing anomaly of upcoming letters (Geiger & Lettvin, 1994; Facoetti et al., 2000; Hawelka et al., 2006; Pernet et al., 2006), or impaired implementation of serial allocation of visual attention (Whitney & Cornelissen, 2005). Alternatively, an extra-phonological difficulty may comprise a domain general difficulty in inhibiting activation of upcoming and already-named items in the array (e.g., Hari et al., 2001) or automatising recognition and retrieval of lexical items (e.g., Nicolson & Fawcett, 1999). It remains a possibility, however, that the findings in Experiment 1 reflect a phonological difficulty. Clarke et al. (2005) suggested that the apparent attentional problem exhibited by dyslexic individuals in RAN might reflect a primary phonological deficit: increased difficulty accessing an appropriate phonological code would tax the limited capacity of the executive system, resulting in a secondary attention deficit.

With the aim of investigating the evidence for extra-phonological processes in RAN (and therefore reading fluency) an approach was required that parsed the influence of phonology from vision, as representative of another major domain in reading, as much as possible. Experiments 2-5 represent our attempt to do this by taxing either phonological or visual processes during RAN using either phonologically or visually confusable letters. Our rationale was that taxing the participant's ability to select the appropriate orthographic or phonological label would indicate a) which domains influenced RAN speed in general, and b) which processes, when aberrant, contributed to the naming speed deficit demonstrated by dyslexic readers.

Experiment 2 sought to replicate findings from Experiment 1 concerning the RAN format, and to also manipulate the RAN content into visually and phonologically confusable trials (using the same items as Compton, 2003, in his unselected reading sample). In addition to replicating the main findings from Experiment 1, results from this study demonstrated that *visually* confusable RAN letters led to slower RTs for both reading groups compared with phonologically confusable RAN letters, suggesting that the ability to visually process and/or select the appropriate graphemic code exerts a greater influence on RAN speed than selecting a phonological code. Our results therefore replicated Compton's findings. Moreover, with reference to the main research question addressed in this thesis, the dyslexic group demonstrated particularly slow RTs in the visual condition. Performance on the Visual Letter set did not vary as a function of the task format, however, suggesting that recent activation of items similar in form to the letter currently being named interfered with matching the target's features to stored orthographic representations. Further, Experiment 2 revealed that visual and phonological versions of RAN contributed variance to word recognition measures.

Experiment 2 was informative in suggesting an influential role for visual information in RAN and building on Compton's findings. To improve on this study, however, Experiments 3 and 4 introduced two additional features: first, in order to exert tighter control over *confusable* item presentation, we presented confusable items adjacently (in pairs) to maximise the confusability of the stimuli and, in the continuous formats, to investigate the effect of parafoveal processing on naming latencies. Second, we introduced baseline conditions, in which the letters were reordered, such that a target with a confusable neighbour in the 'confusable' condition had a dissimilar neighbour in the 'non-confusable' condition. As in

Experiment 2, results from Experiment 3 suggested that visual information influences naming times in RAN, and results in disproportionately increased naming times for dyslexic readers. A comparison across continuous and discrete formats suggested no effects of confusable items specifically in the parafovea. When letter items were chosen with stricter experimental control in Experiment 4, phonological onset and visual information influenced naming times for both reading groups, but only letters with confusable phonological rimes disproportionately increased naming times in the dyslexic group compared with the non-dyslexic group.

Experiments 2-4 therefore yielded an indication of the processes underlying RAN as a measure of the low-level processes involved in reading fluency. In general, visual information influenced naming times for both reading groups, but the dyslexic group in particular. However, the use of total naming times (summed across trials) in these experiments led to inconsistent results. Moreover, it is possible to level critcism relating to the items used to represent 'confusability' in these experiments: each set of items was subsequently deemed insufficiently representative of the confusability it was designed to promote. We concluded that the use of total times in combination with sub-optimal confusability of letter sets led to inconsistencies in the results between experiments, suggesting that gaining answers to our research question would benefit from a new approach.

Experiment 5 therefore comprised a similar design to Experiment 4 (with improved criteria for visual items), but this time, eyetracking methodology was employed. Eyetracking allows a precise measure of *where* and for *how long* the participant is looking at a stimulus in relation to their speech output. In the production literature, experiments using eyetracking during object naming have revealed that participants tend to operate a discrete naming style, in which a phonological label is accessed before participants saccade to the next item (Meyer et al., 1998). Using this methodology, we investigated the total processing time, up to articulation of the letter name. Further, we could measure the processing time on a letter both before and after the eye had made an explicit saccade to the next (confusable or non-confusable) item, measures that indicated the role of parafoveal processing in RAN.

In our view, the design of Experiment 5 was cleanest regarding the selection of letters to represent visual and phonological (onset and rime) domains, which, in addition to the eyetracking methodology, rendered Experiment 5 the pinnacle of our investigation of an extra-phonological deficit in RAN. The results of processing time measures suggested that both phonological onset *and* visual information in RAN influence naming times for *both* reading groups. Further, these measures demonstrated that both reading groups' naming times were susceptible to confusable phonological *and* visual information in parafoveal vision. Findings from processing time measures also suggested that the dyslexic group were slower when parafoveal onset information was difficult to distinguish from foveal information. Critically, measures that included production times (to the point of articulatory onset) showed that dyslexic readers' naming times were disproportionately longer - compared with non-dyslexics' times - when the target was preceded or succeeded by either onset *or* visually similar. These findings suggest that both phonological and visual information play an influential role in RAN and reading fluency.

Taken together, these findings show that phonological and visual information presented in the parafovea influences naming times for both reading groups, suggesting an important role for both domains in reading fluency. An advantage for processing multiple items demonstrated in non-dyslexic groups (Experiments 1 and 3) contrasts with dyslexic readers' comparable naming speeds for single and multiple items, irrespective of the availability of parafoveal information. Experiment 5 demonstrated that dyslexic readers *are* sensitive to parafoveal information, but phonological information in the parafovea in particular interferes with current target processing.

In a measure that also includes processing time to the point of articulatory onset (the *Eye-Voice* span measure; Experiment 5), however, dyslexic readers yield increased naming times for *visually* confusable in addition to phonologically confusable items. Dyslexic readers are therefore particularly susceptible to the effects of visually confusable information, but our findings suggest that the difficulty only emerges in the production phase, when the participant is required to select an appropriate phoneme to match the grapheme. Our conclusion is similar to Pernet et al.'s (2006) proposal that a deficit in dyslexia involves 'higher' visual processes, involving integration of the features of targets and flankers, which impairs selection of an appropriate phonological label.

In Experiments 2-5, we chose to investigate the existence of an extra-phonological deficit in RAN through manipulating visual information. Based on the Wolf and Bowers (1999) naming model, our rationale was that the extra-phonological deficit would either comprise a visual impairment, or a domain general difficulty, which would also influence visual processing. We succeeded in demonstrating that visual information can also influence naming times and impairs dyslexic compared with non-dyslexic naming times. The next step was to investigate whether the visual effect found in several of our experiments reflected an effect within the visual domain *per se*, as opposed to a manifestation of a domain general timing or attention-related deficit. Experiment 6 therefore compared dyslexic and non-dyslexic reading groups on three measures of visual processing that have previously been implicated in dyslexia: motion perception, visual-search and letter position encoding. Dyslexic readers obtained lower accuracy scores on visual-search and letter position encoding, suggesting impairment in the dorsal pathway of the visual system. Performance on these tasks was also related to RAN performance, in addition to non-word and exception word naming. These findings suggest that performance on dorsally mediated tasks involving a search component to some extent mirror the fast visual uptake required in the RAN, implying a specific influence on RAN from within the visual domain.

9.3 Conclusions

This thesis therefore provides evidence of extra-phonological processes in RAN, with findings that visual information a) influences RTs in general and b) is implicated in longer naming times for dyslexic readers. Our findings consistently suggest that both phonological and visual information influence RAN and are key discriminators of reading groups. However, our current findings cannot determine whether the effects obtained in these experiments represent primary influences of phonological and visual processes, or whether both are symptomatic of a domain-general influence. In this section, we speculate how our data can be interpreted within these frameworks before suggesting further studies to elucidate these matters in the final section.

The finding that visual information influences RAN performance is consistent with a visual magnocellular account of dyslexia, and Experiment 6 in particular suggests a link between visual perceptual impairment (involving dorsal stream processing) and performance on the RAN. Other findings gleaned from our experiment, however, suggest that perhaps these ostensibly visual deficits may in fact be manifestations of a domain-general deficit. In the literature on dorsal stream processing (Chapter 8), for example, it is clear that early perceptual stages of visual processing and attentional processing are closely bound. As noted in Chapter 8, late stages of dorsal functioning involve the parietal cortex, which deploys attention across the visual field (e.g., Arguin et al., 1993; Corbetta et al., 1993, 1995). However, Hari et al. (2001) also identify parietal regions as the locus of a domain-general attentional problem in dyslexia (see Chapter 7). Perhaps our findings in Experiment 6 reflect a domain-general attentional difficulty in the dyslexic group, which is manifest in the visual domain. It is also possible that the observed relationship between the visual tests and RAN in Experiment 6 in fact relies on a mutual dependence on working memory rather than speed of visual uptake.

In further support of the domain-general hypothesis, dyslexic readers were found to be generally slower than non-dyslexic readers, irrespective of the experimental condition, across all the experiments presented in this thesis. Such a finding is consistent with impaired attentional capture, leading to a processing speed difficulty in each subsequent processing domain. Similarly, if binding visual and verbal information in close temporal proximity is impaired in the RAN, (e.g., Breznitz, 2003), increasing the likelihood of confusing phonological or visual information in our experiments therefore increased the probability of exacerbating the timing asynchrony in dyslexia. Perhaps our results reflect a domain-general difficulty that, because of the experimental manipulation, manifest in visual and phonological processing difficulty.

The similarity of our findings in both phonological and visual domains also suggests a similar mechanism that may influence both domains rather than independent contributions from within each domain. Moreover, influences on RAN within both domains coincided with the influence of items preceding and succeeding the target on target naming times (Experiment 5). These manipulations also impaired dyslexic compared with non-dyslexic readers' naming times. We suggest that the generality of these findings across domains and across multiple items in the RAN indicate a domain general influence, which is in some way impaired in dyslexic readers. This is not to exclude further influences from either domain, however. Indeed, Wolf and Bowers (1999) propose that specific impairments within phonological and visual domains might prove to be the basis of single deficit subtypes of dyslexia within their double deficit model.

We can only speculate in this section as to the nature of a domain general deficit that impinges on naming speeds in dyslexia. There are several mechanisms which, when impaired, might disrupt the *automaticity* with which letter names are retrieved. The domain-general magnocellular hypothesis (Stein & Walsh, 1997), for example, implicates impaired processing speed across all modalities. On the cognitive level, Hari et al. (2001) have proposed that dyslexic readers demonstrate Sluggish Attentional Shifting (SAS), which cascades from a magnocellular deficit via parietal-lobe-supported attentional capture. Hari et al. (2001) describe impaired inhibitory processes as a result of SAS, which in the RAN could account for the significant influence of items preceding and succeeding the target on target naming times. This deficit could also account for our findings suggesting dorsally-mediated deficits (Experiment 6).

Such an attention deficit might cascade from a different neurological site, however. Cerebellar abnormalities, also implicated in dyslexia could lead to the lack of automaticity demonstrated by dyslexic readers on RAN tasks. The cerebellum is known to be involved in sub-vocalisation of speech (Thach, 1996), and Fawcett and Nicolson (2001) propose that difficulty in sub-vocalisation might impair reading fluency rates (p. 100). In our experiments, a deficit in non-phonological (visual) domains was only found in measures that included the participant's RT to prepare a verbal response, suggesting that articulatory skill might also play a part in determining performance on RAN and reading fluency. As noted in Chapter 2, pause times between items in RAN are more consistently associated with reading group differences than articulatory times of the letter name (e.g., Neuhaus et al., 2001). However, Fawcett and Nicolson (2002) obtained results suggesting that a young dyslexic group showed prolonged articulatory gestures in addition to pause times compared with age and reading-matched controls. An assessment therefore needs to be made concerning the inconsistency in the results relating to articulation times. The task used by Nicolson and Fawcett (2002) comprised repetition of phoneme strings presented auditorily (e.g., /p/ /t/ /k/). Apart from the lack of a visual stimulus, then, there is minimal difference between this task and the RAN, and it is difficult to see why this would differentially influence articulation times. As noted by Fawcett and Nicolson, a large scale study comprising a broad age span of dyslexic and control participants is required, which systematically investigates group differences on articulation times in a number of literacy related tasks. With reference to our current findings, however, we suggest that preparation of the articulatory response is a critical factor in determining RAN performance and discriminating reading groups.

In summary, findings from this thesis indicate the existence of extra-phonological processes on RAN as an indicator of the low-level processes involved in reading fluency on reading groups of varying abilities, but in particular, on individuals with dyslexia. The results reported therefore support Wolf and Bowers' (1999) model of fluency, which emphasises the multi-componential nature of the naming process. The following section outlines experimental designs for continuing this line of research.

9.4 Directions for future research

Wolf and Kennedy (2003) noted that reading involves integrating language with a visual system that has evolved for object recognition. From the same premise, Wolf and Bowers (1999) suggest that the rapidity with which visual symbols can be translated into their constituent sounds influences reading fluency. The experiments reported here support this hypothesis. Our data suggest that both phonological and visual information exert a significant influence on the fluency (as indexed by RAN) of both dyslexic and non-dyslexic reading groups. Both domains are also implicated in dyslexic readers' slower latencies relative to the non-dyslexic groups. As we have already suggested in this chapter, however, there remain a number of questions still to be answered.

First, the current data speaks of dyslexic deficits in attentional, visual and phonological domains. In the interpretation of this data, however, we are faced with the old problem of differentiating between *symptoms* and *causes* of dyslexia (e.g., Nicolson, Fawcett, & Dean, 2001; see also the Introduction to this thesis). Whilst slower processing for the dyslexic groups in these domains indicates a deficit which is perhaps pervasive, we cannot currently locate the root of these deficits. It seems unlikely that they comprise independent, specific deficits in each domain (although independent deficits in each domain would presumably exacerbate the problem or comprise dyslexic 'single-deficit' subtypes according to the double-deficit hypothesis). Rather, the current pattern of results suggest a domain-general deficit in naming speed, occurring at an early processing stage, which cascades to each separate domain. At the cognitive level, this is likely to be an attentional deficit, with an as yet undetermined neurological cause.

Ideally, then, a study is required to experimentally determine the RAN's status as a domain-general versus domain-specific task. Separating these factors experimentally is difficult, but may be possible using the Rapid Alternating Stimulus (RAS) task (Wolf, 1986). This task presents alternating stimuli from different semantic domains (such as letters and numbers). Performance on the task therefore demands rapid *code switching* between semantic domains, placing greater demand on the attentional system. Our current visually confusable and non-confusable items include items from the same semantic domain. Perhaps the next step is to use this as a baseline from which to measure visual similarity and dissimilarity *across* semantic domains. If, for example, RAN comprises a primary attentional deficit (at the cognitive level), we might expect longer RTs in the dyslexic group for visually confusable items across, as compared to within, semantic domains (e.g., across domains: ‘6’ followed by ‘b’; within domains: ‘d’ followed by ‘b’). If, on the other hand, the deficit comprises a primary visual deficit, we could expect similar RTs across groups in both manipulations.

An additional, large scale study might also look at the prevalence of domain-general and domain-specific impairments in RAN. In the current experiments, we were concerned with overall group differences, but given a larger sample, it would be interesting to classify the dyslexic group according to Wolf and Bowers’ (1999) double deficit criterion. Using the design of Experiment 5 on an unselected sample of readers, for example, we could examine whether the proportions in each reading group outlined by Wolf and Bowers are replicated in our experimental manipulations (e.g., the number of participants demonstrating performance one standard deviation below the mean only on visually or phonologically confusable tasks would comprise a single-deficit sub type.) We could subsequently verify these classifications using cognitive and literacy tests to assess whether other characteristics of dyslexia are also present.

Secondly, in this thesis we have been obliged to experimentally investigate the effect of sequencing in RAN on naming times for phonologically and visually confusable letter sets. An important extension of this work is to investigate the influences on processing *individual* letters within the context of a continuous list. An investigation of this kind will soon be possible owing to technological advances in Event Related Potential (ERP) research, which is being merged with eye-movement studies. Although currently in the validation stage, Hutzler (2007), for example, is establishing a method known as Fixation Related Potentials. Rather than being time-locked to 0ms presentation of a stimulus, therefore, the FRP is locked to within 10ms of when the eye fixation stabilises on an item in a continuous stream of stimuli. This technique has the potential to elucidate the time course of orthographic, phonological, semantic and syntactic factors in reading in relation to the attentional cue indicated by the eye fixation. In relation to the current thesis, the FRP would indicate the time course of visual-perceptual, orthographic and phonological processing of each individual item, and whether there is a lag in any of these stages in the dyslexic group.

A question that is fundamental to the importance of RAN relates to whether RAN is in fact a cause or a consequence of reading ability. Clarke et al. (2005), for example, suggested that performance on the RAN is a by-product of the reader's phonological competence when reading. In order to investigate this claim, Maryanne Wolf's lab at Tufts is currently devising a 'baby RAN', for suitable use with pre-literate children. Using this version of RAN, it would be possible to conduct a longitudinal study, in which RAN performance is assessed at a very early (pre-literate) age and again after some explicit literacy tuition. Of interest would be the extent to which RAN performance at time 1 predicted RAN at time 2 (when phonological ability at time 2 had been partialled out).

An important point is the extent to which we can generalise from our current designs using RAN-Letters to other versions of RAN and reading fluency in general. As noted in Chapter 3, we chose the RAN-Letters for these experiments because of its enduring relationship with reading. However, an important criticism of the current work is that the possible combinations of 'confusable' *letters* in RAN are limited, owing to restrictions of the alphabet. Thus, our findings in this thesis were typically based on two confusable versus two non-confusable items in each experiment, which is a limited set compared to the number of items typically used in psycholinguistic research. An important extension of this work which would keep the work within the context of RAN whilst allowing a broader stimulus set would be to use short, frequent words instead of individual letters. Because of the potential for confounding the effects of automaticity with decoding problems in the dyslexic group, however, it would be necessary to have highly stringent control over items in addition to extensive pre-testing in order to avoid grapheme-to-phoneme reading strategies as much as possible.

It would also be interesting to investigate whether our current findings endure in more semantic versions of RAN, such as object naming. In particular, a replication of Experiment 5 using degraded / fully contoured objects (similar to Meyer et al.'s 1998 design) would indicate a) whether we replicate Meyer et al.'s finding of discrete naming in the RAN context, in which parafoveal processing is possible and b) whether dyslexic readers also show disproportionately longer latencies when the visual system is taxed in a non-orthographic task. Thus, we should learn whether the visual difficulties observed in Experiment 5 are pervasive in the visual system, or whether they refer in particular to problems in orthographic processing.

We should also stress that in using the RAN, this thesis represents the low-level components (attentional, visual and phonological processing) involved in reading fluency. Although RAN consistently predicts reading fluency (Bowers, 1993, 1995; Bowers & Swanson, 1991; deJong & van der Leij, 1999; Kirby, Parrilla, & Pfeiffer, 2003 Young & Bowers, 1995), it should be borne in mind that reading text also involves top-down influences from contextual factors, syntax and phonological decoding. We suggest that a truly comprehensive study of reading fluency, given sufficient time and resources, would trace reading fluency from its neurological origin (using fMRI scanning, for example) through perceptual and cognitive stages (represented by RAN) to reading passages of text.

This thesis set out to examine the evidence for extra-phonological deficits in RAN-Letters performance, as indicative of the low-level processes involved in reading fluency. Six experiments showed that in general, both phonological and visual information are influential low-level factors, which can determine how fluently lexicalised items can be retrieved. Further, processing in both domains are implicated in the naming speed deficit characteristic of dyslexia. These findings provide evidence for the multi-componential nature of fluency, and suggest that the RAN deficit in dyslexic readers is domain-general in nature.

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Appendix A

Experiments 1-6: Items used in the non-word reading test

1. Chur
2. Knap
3. Tive
4. Barp
5. Stip
6. Plin
7. Frip
8. Poth
9. Vasp
10. Meest
11. Shlee
12. Guddy
13. Skree
14. Felly
15. Clirt
16. Sline
17. Dreef
18. Prain
19. Zint
20. Bloot
21. Trisk
22. Kelm
23. Strone
24. Lunaf
25. Cratty
26. Trober
27. Depate
28. Glant
29. Sploosh
30. Dreker
31. Ritlun
32. Hedfert
33. Bremick
34. Nifpate
35. Brinbert
36. Clabom
37. Drepnort
38. Shratted
39. Plofent
40. Smuncrit
41. Pelnador
42. Fornalask
43. Fermabalt
44. Crendimoke
45. Emulbatate

Appendix B

Experiments 2-6: Items used in the exception word reading test

1. Ocean
2. Iron
3. Island
4. Busy
5. Sugar
6. Truth
7. Whom
8. Tongue
9. Rhythm
10. Stomach
11. Wounded
12. Sword
13. Anchor
14. Echo
15. Chorus
16. Dough
17. Ache
18. Ninth
19. React
20. Tomb
21. Vague
22. Colonel
23. Drought
24. Bought
25. Trough
26. Depot
27. Aisle
28. Bouquet
29. Foreign
30. Yacht
31. Chauffeur
32. Sergeant
33. Suede
34. Gauge
35. Bureau
36. Circuit
37. Schedule
38. Encore
39. Heirloom
40. Champagne
41. Distraught
42. Sovereign
43. Righteous
44. Benign
45. Baroque

Appendix C

Published article based on Experiment 6

Currently in press in *Dyslexia: An International Journal of research and practice*.

(Please see overleaf)

Appendix A

Experiments 1-6: Items in the non-word reading test

1. Chur
2. Knap
3. Tive
4. Barp
5. Stip
6. Plin
7. Frip
8. Poth
9. Vasp
10. Meest
11. Shlee
12. Guddy
13. Skree
14. Felly
15. Clirt
16. Sline
17. Dreef
18. Prain
19. Zint
20. Bloot
21. Trisk
22. Kelm
23. Strone
24. Lunaf
25. Cratty
26. Trober
27. Depate
28. Glant
29. Sploosh
30. Dreker
31. Ritlun
32. Hedfert
33. Bremick
34. Nifpate
35. Brinbert
36. Clabom
37. Drepnort
38. Shratted
39. Plofent
40. Smuncrit
41. Pelnador
42. Fornalask
43. Fermabalt
44. Crendimoke
45. Emulbatate

Appendix B

Experiments 2-6: Items in the exception word reading test

1. Ocean
2. Iron
3. Island
4. Busy
5. Sugar
6. Truth
7. Whom
8. Tongue
9. Rhythm
10. Stomach
11. Wounded
12. Sword
13. Anchor
14. Echo
15. Chorus
16. Dough
17. Ache
18. Ninth
19. React
20. Tomb
21. Vague
22. Colonel
23. Drought
24. Bought
25. Trough
26. Depot
27. Aisle
28. Bouquet
29. Foreign
30. Yacht
31. Chauffeur
32. Sergeant
33. Suede
34. Gauge
35. Bureau
36. Circuit
37. Schedule
38. Encore
39. Heirloom
40. Champagne
41. Distraught
42. Sovereign
43. Righteous
44. Benign
45. Baroque

Appendix C

Article based on Experiment 6. Currently in press in *Dyslexia: An International Journal of research and practice*.

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Visual Deficits in Developmental Dyslexia: Relationships between Non-linguistic Visual Tasks and their Contribution to Components of Reading

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Developmental dyslexia is often characterized by a visual deficit, but the nature of this impairment and how it relates to reading ability is disputed (*Brain* 2003; **126**: 841–865). In order to investigate this issue, we compared groups of adults with and without dyslexia on the Ternus, visual-search and symbols tasks. Dyslexic readers yielded more errors on the visual-search and symbols tasks compared with non-dyslexic readers. A positive correlation between visual-search and symbols task performance suggests a common mechanism shared by these tasks. Performance on the visual-search and symbols tasks also correlated with non-word reading and rapid automatized naming measures, and visual search contributed independent variance to non-word reading. The Ternus task did not discriminate reading groups nor contributed significant variance to reading measures. We consider how visual-attention processes might underlie specific component reading measures. Copyright © 2007 John Wiley & Sons, Ltd.

Keywords: dyslexia; magnocellular; dorsal stream; letter position encoding

INTRODUCTION

Developmental dyslexia is a term used to define individuals with lower reading ability than their developmental peers despite normal intelligence and adequate educational provision (Rutter & Yule, 1975).

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Dyslexia is highly prevalent, but its cause is not yet fully understood. We investigate how impaired visual processing might translate into a reading deficit, specifically how tasks measuring visual-attention functioning might predict difficulties with the visual requirements of reading: for example, the ability to encode letter position within a string, as well as difficulties with specific components of reading, such as processing speed, decoding and exception word recognition.

Magnocellular Deficits in Dyslexia

Dyslexic readers consistently show deficits in phonological decoding and awareness (Snowling, 2000), but some affected individuals also have visual difficulties. Early research by Lovegrove suggested that visual difficulties stem from impaired 'transient' visual pathways in the lateral geniculate nucleus (LGN) (e.g. Lovegrove, Bowling, Badcock, & Blackwood, 1980; Slaghuis & Lovegrove, 1984). The LGN comprises two pathways, which run in parallel and to a large degree remain separate in their projection to the primary cortex (V1). Parvocells process information of form and colour, which is not demonstrably impaired in dyslexia (e.g. Lovegrove *et al.*, 1980). Magno cells detect transient movement information in the visual field (Galaburda & Livingstone, 1993).

The transient visual deficits described by Lovegrove have since been attributed to the magnocellular pathway (see Stein & Walsh, 1997). A number of psychophysical studies demonstrate impaired performance in dyslexic compared with non-dyslexic readers on measures of magnocellular processing, such as sensitivity to dynamic visual stimuli (Richardson, Mason, & Stein, 1995; Livingstone, Rosen, Drislane, & Galaburda, 1991; Lovegrove *et al.*, 1980; Lovegrove, Martin, & Slaghuis, 1986; Mason, zCornelissen, Fowler, & Stein, 1993), ability to detect coherent motion in random dot kinematograms (Cornelissen *et al.*, 1995, 1998; Pammer & Wheatley, 2001), and ability to perceive global movement at short interstimulus intervals (ISIs) on a Ternus illusion task (Cestnick & Coltheart, 1999; Slaghuis, Twell, & Kingston, 1996).

Stein and Walsh (1997) and Stein and Talcott (1999) proposed that magnocellular irregularity causes unstable fixations during reading, leading to inaccurate processing of orthographic information. However, findings relating magnocellular deficits and dyslexia have not been consistently replicated, nor are they found on multiple task comparisons (Evans, Drasdo, & Richards, 1994; Walther-Muller, 1995). Several studies also demonstrate an important role for visual attention but find no evidence of an additional magnocellular deficit (Iles, Walsh, & Richardson, 2000; Roach & Hogben, 2004; Steinman, Steinman, & Garzia, 1996; see Ramus (2003) and Skottun (2005) for reviews of the evidence relating to magnocellular deficits in dyslexia). Moreover, recent attempts to relate cued visual-search performance with more standard measures of magnocellular functioning (such as global dot motion; e.g. Cornelissen *et al.*, 1998) failed to demonstrate a relationship between these tasks (Roach & Hogben, 2004).

The Dorsal Deficit Hypothesis

The magnocellular hypothesis of developmental dyslexia has, therefore, been substantially revised to include a stronger role for visual attention. From the primary cortex, two visual streams are known to project information to other cortical areas. The dorsal stream (dominated by magno-inputs) projects to V2 and to V5 and the parietal cortex. Information carried by this stream is considered critical in the pre-attentive control of spatial selection. In contrast, the parvo-dominated ventral stream projects to areas V2, V3, V4 and the inferotemporal cortex, and operates a more detailed analysis of form, colour and texture (Vidyasagar, 1999). Recent research proposes that dyslexic visual deficits may be located in the dorsal stream (Pammer & Vidyasagar, 2005).

Vidyasagar (1999) and Pammer and Vidyasagar (2005) suggest that different processing styles exhibited by dorsal and ventral visual pathways reduce the computational load on the visual system that might arise if both pathways operated simultaneously on the same visual input features. The dorsal stream acts as an 'attentional spotlight', guiding visual attention to salient components of the visual stimulus. A decision is made concerning regions of interest which is followed by more detailed (ventral) processing of that region (Pammer & Vidyasagar, 2005). In reading, the dorsal stream allocates attention to appropriate areas of text, providing sufficient feedback to the ventral stream to allow fine-grained analysis of letters (Pammer & Vidyasagar, 2005). Empirical findings that dorsal functioning is critical in the pre-lexical stages of word processing support this account (Mayall, Humphreys, Mechelli, Olson, & Price, 2001). A dorsal stream *deficit* might therefore impede smooth attentional focus on orthographic items, disrupting the visual discrimination of letters that is accomplished by the ventral stream (Pammer & Vidyasagar, 2005).

Contribution of Dorsal Functioning to Reading

Late stages of dorsal stream functioning involve the parietal cortex, which serves to deploy and control visual attention across different regions of the visual field (e.g. Arguin, Joanette, & Cavanagh, 1993; Corbetta, Miezin, Shulman, & Petersen, 1993, 1995). The *conjunction* search task, in which a target stimulus differs from distracter items in two or more ways, is a means of testing parietal cortex functioning. Typically, reaction times on conjunction tasks increase linearly with increased set sizes, suggesting that each stimulus is processed in turn, requiring a shift in visual attention (e.g. Ashbridge, Walsh, & Cowey, 1997). When compared with conjunction tasks, child and adult groups of dyslexic and average readers show reduced accuracy levels (Buchholz & McKone, 2004; Casco & Prunetti, 1996; Iles *et al.*, 2000; Vidyasagar & Pammer, 1999). Low accuracy levels reflect a reduced ability in the parietal cortex to shift attention across the visual field (Buchholz & McKone, 2004). However, in tasks believed to be mediated by the ventral stream, requiring attention to fine spatial detail, such as visual acuity, good and poor readers perform equally well (Buchholz & McKone, 2004; Pammer & Wheatley, 2001).

The precise impact of a dorsal stream deficit on reading remains elusive, however. Pammer, Lavis, and Cornelissen (2004) investigated whether dorsal stream functioning influences reading ability via letter-position encoding. Letter-position encoding refers to the readers' sensitivity to the relative locations of orthographic items within a string; less skilled readers are more inaccurate in judging item position compared with highly skilled readers (e.g. Mason, 1980). One measure of letter-position encoding is the 'symbols task', in which symbol

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strings are briefly presented to the participant; the participant memorizes the position of each item in the string and then selects the correct string from a forced choice of two alternatives. Using letter-like symbols eliminates lexical influences, yielding a measure of how well the relative positions of items are visually encoded. Children with dyslexia give fewer correct responses in this task than non-dyslexic readers (Pammer, Lavis, Hansen, & Cornelissen, 2004). Furthermore, performance on the task significantly predicts word recognition ability in adults (Pammer, Lavis, Cooper, Hansen, & Cornelissen, 2005).

Previous research correlated performance on the symbols task with a measure of dorsal functioning—frequency doubling technology, which involves threshold measurement for pattern detection—in order to investigate the relationship between dorsal functioning and letter-position-encoding mechanisms (Pammer, Lavis *et al.*, 2004). Pammer *et al.* found no relationship between these tasks, but both measures were related to reading. Pammer *et al.* suggest a division of labour for spatial processing in reading, such that dorsal functioning operates a coarse, peripheral analysis of text independently of the detailed, spatial analysis provided by ventral processes that underpins letter-position encoding.

Aims of the Present Study

We examine an alternative: that dorsal-mediated pre-attentive analysis of lexical spatial relationships also contribute to letter-position encoding, as well as operating a coarse coding mechanism in reading. If the ability to swiftly and accurately encode letter position involves efficient interaction between dorsal and ventral visual processes, then a deficit at the dorsal level would impede smooth attentional flow, impairing the ability to sequence letter items (Pammer & Vidyasagar, 2005). It may be more fruitful to view letter-position encoding as a function of the interaction between dorsal and ventral processes. Hence, we predict that the letter-position encoding performance should correlate with the performance in tasks in which pre-attentive selection of a target item allows a subsequent fine-grained discrimination of its spatial properties.

To address this hypothesis, we compared adult dyslexic and non-dyslexic readers' performance on three different visual tasks in order to investigate the visual processes underpinning letter-position encoding and to examine the contribution of visual processes to component skills of reading.

We measured letter-position encoding ability using the symbols task, which has previously demonstrated discrepancies between dyslexic and non-dyslexic groups (Pammer, Lavis, Hansen *et al.*, 2004). We measured visual attention using a cued visual-search attention task involving exogenous cueing of a target presented amongst identical distracters (see Roach & Hogben, 2004). Exogenous cueing involves a peripheral cue that precedes a target by a short delay; provoking an involuntary shift in attention towards the location of the subsequent target (e.g. Facoetti, Lorusso, Paganoni, Umilta, & Mascetti, 2003; Warner, Juola, & Koshino, 1990). Exogenous cueing facilitates non-dyslexic readers' accuracy in predicting target location, but yields no such benefit for dyslexic readers (e.g. Facoetti, Turatto, Lorusso, & Mascetti, 2001; Roach & Hogben, 2004). In our version of the cued visual-search task, participants had to identify the target's tilt direction as well as its location. The attention allocated to the target region by dorsal processes would then allow rapid target selection in the ventral stream, given the unique tilt property of the target amongst vertical distracters (Vidyasagar, 1999).

A third 'Ternus' task involved magno-dominated dorsal functioning (Skottun, 2000). In early studies, Lovegrove used sine wave gratings interspersed by a blank ISI and measured the participants' ability to perceive the blank ISI (e.g. Martin & Lovegrove, 1988; Slaghuis & Lovegrove, 1984). Failure to perceive the blank ISI was originally interpreted as *visual persistence* of the first item at the time the second was displayed: when stimulus 2 was presented, the magnocellular system failed to override form (parvo) information of stimulus 1 (Breitmeyer & Ganz, 1975).

Tasks based on this principle have yielded a substantial body of evidence that poor readers have longer-lasting visual persistence than good readers: they require longer ISIs than good readers in order to perceive group movement (e.g. Cestnick & Coltheart, 1999; Martin & Lovegrove, 1984, 1988; Patterson *et al.*, 1988; Slaghuis & Lovegrove, 1984, 1985, 1986a, b; Slaghuis *et al.*, 1996; Winters *et al.*, 1989). One such task is the Ternus task (Ternus, 1938), which comprises three horizontally aligned squares presented briefly (frame 1), then presented again moved one imaginary square's breadth to the right (frame 2). The frames are alternated a number of times. Two types of motion detection ensue, depending on the length of ISIs between frames: short ISIs result in 'element' (or single) movement perception, in which the leftmost square is perceived to jump to the right-hand side from frame 1 to frame 2, whereas longer ISIs ($\sim$ 50 ms and above) result in 'global' (or group) movement perception, in which all three squares move as a group to the right. Breitmeyer and Ritter (1986) hypothesized that the onset of group movement perception marks the point at which magnocellular functioning terminates visual persistence by inhibiting the parvocellular system. However, Kramer and Rudd (1999) demonstrated that an element movement can be perceived in the absence of visual persistence. Skottun (2000) proposed that a single mechanism may govern both perceptual element and group movement perception, but they reflect different levels of processing: whilst element movement reflects subcortical processes, group movement is located at or beyond the primary visual cortex (see Skottun, 2000).

Based on previous findings, we predicted group differences in all three visual tasks: non-dyslexic readers should give more correct responses than dyslexic readers on the symbols and visual-search tasks, and should require shorter ISIs to detect group movement in the Ternus task. Moreover, performance relationships between the different tasks should be informative about the visual processes underlying letter-position-encoding ability. If dorsal functioning (indicated by performance on the Ternus task) is involved in letter-position-encoding ability, the Ternus should predict performance on the symbols task. Similarly, if visual-attention processes (indicated by performance on the visual search task) underlie letter-position encoding, specifically the efficiency of communication between dorsal and ventral processes, then the visual-search task should contribute variance to the symbols task.

Finally, we measured contributions of the symbols, visual-search (cued condition) and Ternus tasks to specific reading component measures (phonological decoding, exception word reading, rapid naming and spelling). Our primary interest was whether performance on the three visual tasks would predict the same or different reading component measures, indicating common or independent contributions to reading (Pammer, Lavis *et al.*, 2004).

METHOD

Participants

Thirty-eight University of Edinburgh students participated for payment (19 dyslexic and 19 non-dyslexic chronological-age-matched). Mean age was 22.2 years for the dyslexic group (range: 18 years and 6 months to 23 years and 9 months) and 23.1 years for the non-dyslexic group (range: 18 years and 2 months to 25 years and 10 months). There were 9 males and 10 females in each group. Dyslexic participants were formally assessed by an educational psychologist or by the University Disability Office.

Materials and Procedure

Visual tests were presented using E-prime version 2 software (Schneider, Eschman, & Zuccolotto, 2002) on a Windows PC and were displayed on an Iiyama HM703UT VisionMaster Pro 413 RM monitor with a resolution of 1024 × 768 pixels. Participants sat at a distance of approximately 60 cm from the screen.

Component Reading and General Cognitive Measures

We used the spelling section of the Wide Range Achievement Test-3 (WRAT-3) (Wilkinson, 1993) and two independent word recognition measures: 'Phonemic Decoding Efficiency' from the Patient Assessment Training System (PATSy) battery (Lum, Cox, Kilgour, Snowling, & Haywood, 2005), involving non-word items 4–10 letters long (e.g. *knap*); and a list of 'exception' words from Wile and Borowsky (2001) (e.g. *yacht*). Words (vertical visual angle: approximately 3°) were presented individually on a computer monitor, and the mean number of correct responses for each participant was calculated. We measured the naming speed using rapid automatized naming (RAN; Denckla & Rudel, 1976) measures. Trials were presented in grids of 30 (10 × 3) letters, with a visual angle of 0.5° per letter and 3° between letters. An average RT measure was calculated from performance on eight trials. On both the word-recognition and naming-speed tasks, participants were required to name each word/letter as quickly and accurately as possible. On the digits forwards and digits reversed sections of the Bangor Dyslexia Test (Miles, 1993), which tested working memory, participants had to repeat in the same or reversed order increasingly long strings of digits produced by the experimenter. The British Dyslexia Association (BDA) checklist (Vinegrad, 1994) provided a subjective checklist of dyslexia characteristics. Finally, the short form of the Advanced Progressive Matrices tested differences in Performance IQ (Raven, 1958).

Visual Tasks

The Symbols Task

A symbol string comprised five adjacent symbols from a selection of 20, yielding a vertical angle of 2.5° and an angle of 5° horizontally. Each symbol comprised a similar number of vertical and horizontal lines to alphabetic letters, but with minimal similarity to actual letters. This design is similar to Pammer, Lavis *et al.*

(2004), but whereas these authors used white symbols on grey, we presented items in black type on an off-white background to mimic normal contrast characteristics of reading. Target strings were presented for 100 ms, followed by a mask for 100 ms. Two symbol strings were next presented one above the other (see Figure 1), yielding a forced choice decision of which they had seen. Within-string symbol swaps comprised one-third 2nd and 3rd swaps, one-third 3rd and 4th swaps, and one-third 2nd and 4th swaps in random order, comprising 60 trials in total. Ten practice items preceded the experimental session.

The Visual-search Task

Target and distracter items were presented for 100 ms per trial in a circular display surrounding a central fixation cross at a visual angle of 5° (see Figure 2). A target comprised off-vertical items (tilting 10° either to the right, e.g. // or the left, e.g. \\) similar to the grating patches used by Roach and Hogben (2004). Distracters were vertical items (||). Targets and distracters were controlled for size (font 18) and were black on an off-white background. Each stimulus subtended a visual angle of 0.5°, and one target was presented per trial. Participants saw a fixation cross for 100 ms. On half the trials at each set size, this was followed by a 30 ms cue in the exact position of the subsequent target item; on the other half,

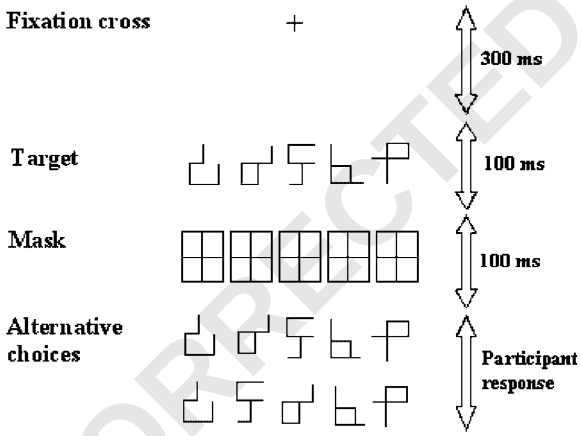

Figure 1. Example trials of the symbols task.

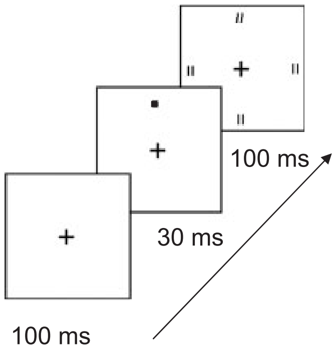

Figure 2. Example trial of the visual-search task in the cued condition.

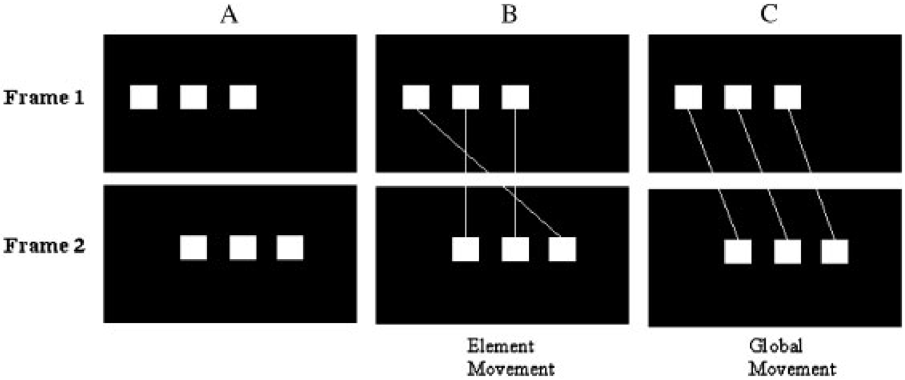

Figure 3. Example element (B) and global (C) perceptions of movement on the Ternus task.

there was no cue. Between trials, on-screen instructions prompted participants to indicate the direction of tilt by pressing either of two buttons. Stimulus sets (including target and distracters) were blocked according to stimulus set size (2, 4, 8 and 16), yielding a total of 160 trials. Eight practice items (2 of each set size) were preceded the experimental session.

The Ternus Task

Three white squares were presented on a black background. The visual angle was identical for the side lengths and the distance between each square (3°). One trial consisted of eight alternations of two display frames. The first display frame presented three squares in a fixed screen position; in the second, the leftmost square was transferred to the rightmost position, whilst the position of the other two squares remained constant. Figure 3 demonstrates the different ways of perceiving movement of squares in the Ternus task: element movement is perceived at short ISIs (column B), whilst global movement is perceived at longer ISIs (column C). The duration of each display frame was 55 ms, with varying ISI length between the display frames per trial: 8, 16, 24, 32, 40, 48, 56, 64, 72 and 80 ms (8 ms steps as opposed to 8.3 ms steps used in Cestnick and Coltheart (1999); these figures also take into account the screen refresh rate). ISI length was randomized across the experiment. There were ten trials in each ISI condition, yielding a total of 100 trials per participant. The experiment was self-paced; participants were presented with a forced choice decision of ‘global’ or ‘element’ movement perception, which they indicated by pressing either of two buttons on the button box. Ten practice trials (one of each ISI length) preceded the experimental session.

RESULTS

Demographic Characteristics of Group

We compared the dyslexic and non-dyslexic reading groups on a number of component reading skills and general cognitive measures. *T*-tests revealed group differences on the spelling section of the WRAT-3 (Wilkinson, 1993), non-word decoding and exception word tasks, rapid automatized naming, the British Dyslexia Association test, and backward digit span (see Table 1). Equal variances could not be assumed for spelling, non-word nor exception word tasks, due to a larger spread of scores in the dyslexic group. On these measures, we report t-values corrected for unequal variances.

Eighty per cent of the dyslexic sample demonstrated a phonological deficit, and 55% a whole-word recognition deficit, defined as non-word-decoding and exception-word scores 1 standard deviation below the non-dyslexic mean, respectively. Figure 4 demonstrates the spread of scores for dyslexic and non-dyslexic readers on non-word and exception word reading, with a trend for positive overlap on these measures. However, Figure 4 also demonstrates that 5–9 of the dyslexic groups obtained scores that are comparable with the non-dyslexic group, suggesting that they may have compensated for their reading difficulties. To ensure that any group differences were attributable to differences between dyslexic and non-dyslexic readers, we carried out two sets of analyses, first comparing dyslexic and non-dyslexic readers, and then 'high' versus 'low' scorers on the non-word decoding task. We obtained the same pattern of results across both analyses[1] and hence report only the dyslexic versus non-dyslexic analyses.

We measured frequency of correct responses for both the symbol-string and visual-search tasks, including individual mean values for each set size and for the cued and uncued conditions, and frequency of reported 'global movement' perception for the Ternus task (means and standard deviations are reported in Table 2).

To establish whether the visual tasks could distinguish between groups of skilled and reading-disabled readers, we first analysed group differences.

A between-participants one-way ANOVA (dyslexic versus non-dyslexic) on the number of correct responses in the symbols task demonstrated an effect of Group ($F(1, 36) = 5.42$, $p < 0.05$). Table 2 shows that there were more correct responses in the control group than in the dyslexic group.

A repeated measures $2 \times 2 \times 4$ ANOVA with the levels Group (dyslexic versus non-dyslexic), Cue (cue versus no cue) and stimulus Set size (2, 4, 8, 16 items) on the number of correct responses in the visual-search task yielded a main effect of Group ($F(1, 36) = 9.83$, $p < 0.01$): Table 2 shows that dyslexic participants gave fewer correct responses than non-dyslexic participants. There was also a main effect of Set size ($F(3,108) = 66.03$, $p < 0.001$); performance decreased as a function of Set size (all differences significant at $p < 0.01$) (see Figure 5). However, there was no main effect of Cue ($F = 0.24$, $p = 0.63$) nor a Group × Cue ($F = 0.89$, $p = 0.35$) or Group × Set size interaction ($F = 1.77$, $p = 0.16$). There was, however, a significant Cue × Set size interaction ($F(3, 108) = 3.28$, $p < 0.05$); Figure 5 suggests that the presence of a cue was more likely to induce a correct response for smaller rather than larger set sizes.

We analysed the number of group-movement responses in the Ternus task using a 2×10 ANOVA with the levels Group (dyslexic versus control) and ISI (8, 16, 24, 32, 40, 48, 56, 64, 72, 80 ms). There was no main effect of Group ($F = 0.644$, $p = 0.428$) (see Figure 6). Hence there was no greater propensity for non-dyslexic participants to begin detecting group movement at shorter ISIs than dyslexic participants. There was, however, a main effect of ISI

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Table 1. Reading group differences on component reading measures and general cognitive ability; standard deviations in parentheses

Variable	Group					Cohen's *d*
	Dyslexic		Non-dyslexic			
	Mean (SD)	Range	Mean (SD)	Range	*t*	
WRAT-3 spelling: standard score	94.90 (6.23)	63–114	116.6 (6.26)	105–129	5.8**	−‘4.94
BDT digits forwards: span	9.22 (2.23)	4–12	9.84 (2.39)	5–12	0.9	−0.36
BDT digits backwards: span	3.22 (1.62)	0–6	4.95 (1.18)	2–6	4.2*	−2.04
Non word reading: errors	10.43 (6.62)	0–29	1.93 (2.77)	0–8	5.4*	4.25
Exception word reading: errors	3.94 (3.70)	0–14	1.25 (1.44)	0–5	3.3*	2.63
Rapid automatized naming: latency (ms)	17 425 (3570)	12 546–26 754	12 376 (2251)	9802–17 678	5.0*	3.17
Ravens PM: set 1 (correct)	11.25 (1.29)	6–12	11.00 (1.35)	9–12	0.3	0.18
BDA checklist: mean number	12.05 (3.47)	5–12	3.05 (2.58)	4–12	8.8*	2.94

Note: BDT = Bangor Dyslexia Test; BDA = British Dyslexia Association; Ravens PM = Raven's Advanced Progressive Matrices; *$p < 0.01$, **$p < 0.001$.

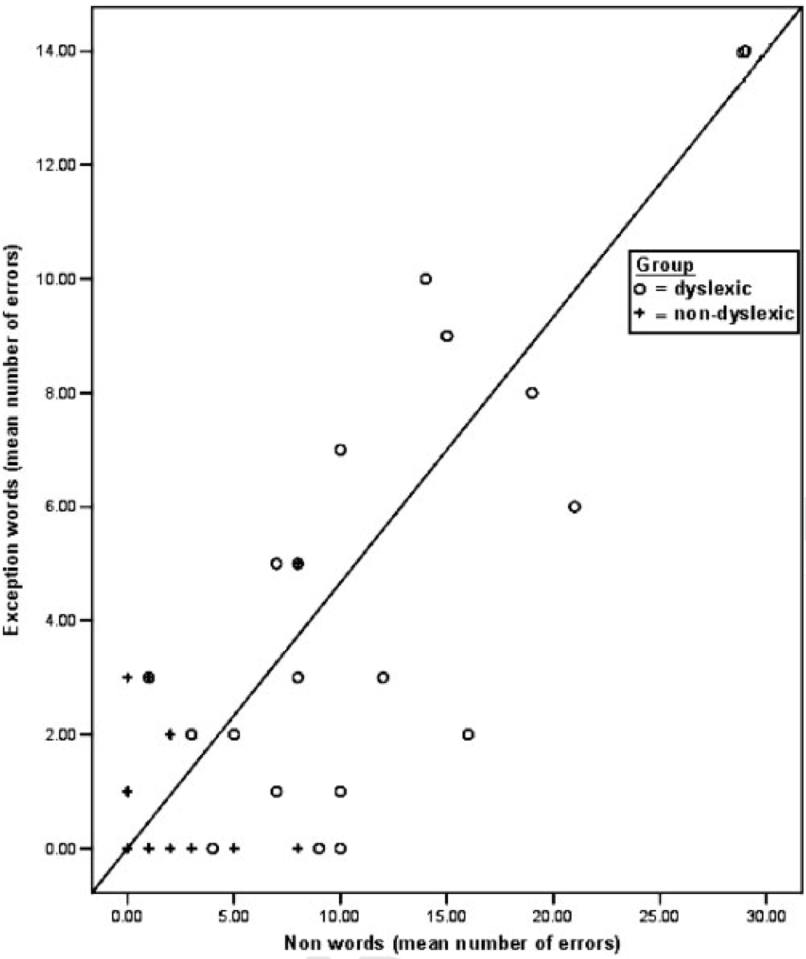

Figure 4. Distribution of mean error rates on non-word and exception word reading for dyslexic and non-dyslexic readers.

($F(9, 324) = 194.76$, $p < 0.001$): overall, participants reported higher incidence of group movement at longer ISIs. There was no interaction between group and ISI ($F = 0.40$, $p = 0.93$).

We next investigated the relationships between the visual tasks, and between these tasks and literacy. Because our goal was to investigate whether the dorsal stream mediates skills such as letter-position encoding and component reading skills, only responses for the cued condition of the visual-search task, in which an involuntary shift in attention indicative of dorsal stream processing occurred (Vidyasagar, 1999), were entered into the analysis. Non-word reading, exception word reading and rapid automatized naming demonstrated positively skewed distributions and were corrected for normality before analysis using a log transfer. Table 3 reports results of a correlation analysis including the three visual tasks and the four component reading measures. Performance on the visual-search and the symbols tasks is significantly correlated. Furthermore, both visual-search and symbols performance correlate with non-word reading and RAN speed.

Table 2. Reading group differences on the symbols, visual-search (across all set sizes) and Ternus tasks (across all ISIs); standard deviations in parentheses

Task	Group						*N* trials	Cohen's *d*
	Dyslexic			Non-dyslexic				
	Mean (SD)	%	Range	Mean (SD)	%	Range		
Symbols: *N* correct	34.88 (7.26)	58	26–45	41.81 (7.74)	81	29–59	60	−0.92
Visual-search (cue): *N* correct	13.95 (2.55)	35	8.75–17.5	16.42 (1.77)	41	13.5–19	80	−1.12
Visual-search (no cue): *N* correct	14.50 (1.94)	36	10.5–17.5	16.39 (1.73)	42	12.75–18.75	80	−1.02
Ternus: *N* perceived global movement	48.40 (12.10)	48	27–68	50.95 (8.98)	51	39–76	100	−0.23

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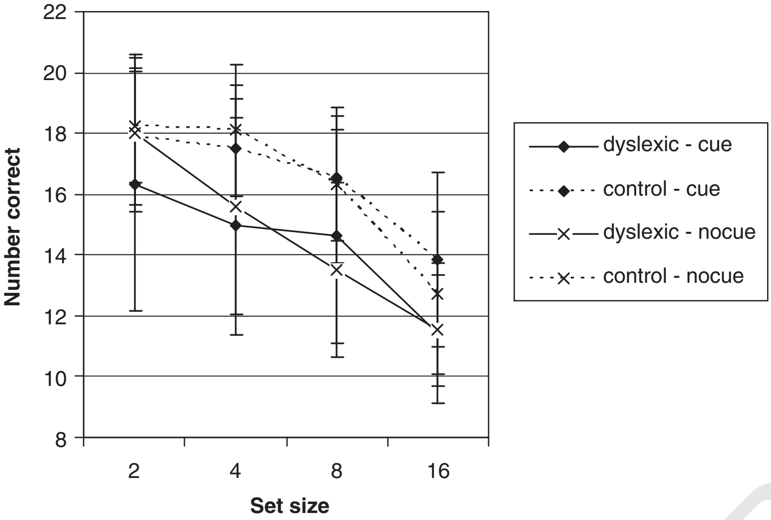

Figure 5. Mean number of correct responses as a function of set size across cued and uncued condition (standard deviations represented by error bars).

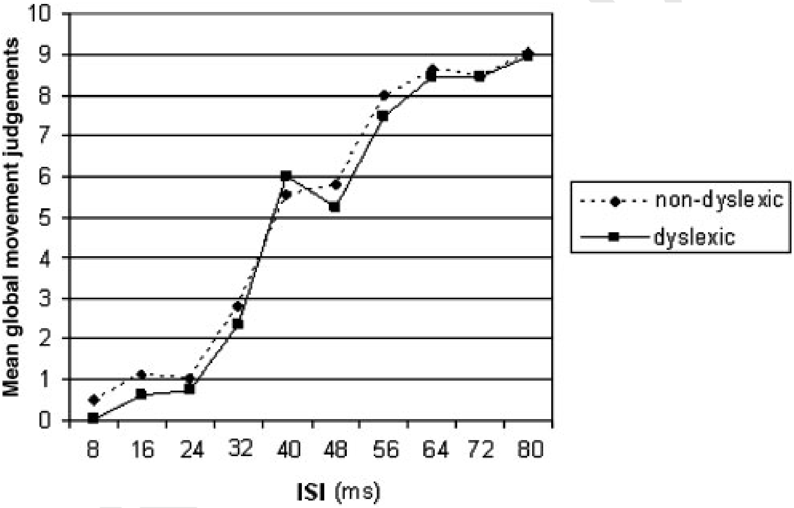

Figure 6. Mean global movement judgements as a function of ISI across reading groups.

A simultaneous multiple linear regression analysis, with visual-search and Ternus task performance as the independent variables and symbols task performance as the dependent variable, investigated inter-task relationships. Neither visual-search nor Ternus performance contributed significant unique variance to performance on the symbols task. However, whilst the visual-search task approached significance ($t = 1.83$, $p = 0.07$), the Ternus task did not ($t = 0.31$, $p = 0.76$) (see Table 4). Despite the significant correlation between symbols and visual-search task performance, the ability on visual search did not contribute unique independent variance to letter-position encoding.

Table 3. Correlation matrix of all variables

	Symbols	Visual search	Ternus	Non-words	Exception words	RAN
Symbols	—					
Visual search	0.296*	—				
Ternus	0.050	0.003	—			
Non-words	−0.291*	−0.416**	−0.015	—		
Exception words	−0.120	−0.134	0.043	0.507**	—	
RAN	−0.282*	−0.275*	0.031	0.477**	0.376**	
Spelling	0.213	0.102	−0.146	−0.654**	−0.463**	−0.581**

Note: *$p<0.05$; **$p<0.01$; (95% confidence intervals for significant correlations).

Table 4. Visual search and Ternus task scores regressed on symbols performance

Variable	*B*	SE *B*	*β*	R^2	*F*
Symbols				0.09	1.28
Constant	20.79	10.50			
Visual search	1.01	0.55	0.29		
Ternus	0.37	1.22	0.05		

A series of simultaneous multiple linear analyses determined the extent to which the three visual tests predicted different reading component measures (see Table 5). Predictors in each analysis comprised the number of correct responses for the visual-search task (cued condition); the number of correct responses for the symbols tasks; and the reported number of 'global' movements reported in the Ternus task. Dependent variables on separate analyses comprised the number of errors in phonological decoding (non-word naming); whole word recognition (exception word naming); reaction time (RT) for RAN; and standardized spelling scores (WRAT-3).

The analyses showed that visual-search task performance contributed significant unique variance to phonological decoding ($t = 2.26$, $p<0.05$), but none of the tasks contributed significant unique variance to exception word reading, rapid automatized naming or spelling.

DISCUSSION

Reading Group Differences on Visual Tasks

We measured visual deficits in dyslexia and their impact on reading by comparing the performance of high-performing adult dyslexic readers to chronological-age-matched non-dyslexic readers on three visual tasks indexing different aspects of visual processing, and on four measures indexing different reading component measures. Our results suggest that there are robust differences in visual processing between dyslexic and non-dyslexic readers, even in these high-functioning samples, and that some of these differences are associated with specific impairments on reading component measures.

Table 5. Symbols task performance regressed on phonological decoding, exception word recognition, rapid automatized naming and spelling

Variable	*B*	SE *B*	*β*	R^2	*F*
Phonological decoding					
Constant	2.12	0.58		0.45	2.90*
Symbols	−0.01	0.01	−0.18		
Visual search	−0.07	0.03	−0.36*		
Ternus	−0.00	0.07	−0.01		
Exception word naming				0.03	0.31
Constant	0.74	0.49			
Symbols	−0.00	0.01	−0.09		
Visual search	−0.02	0.03	−0.11		
Ternus	−0.02	0.05	0.05		
RAN				0.35	1.57
Constant	4.39	0.143			
Symbols	−0.00	0.00	−0.22		
Visual search	−0.01	0.01	−0.21		
Ternus	0.00	0.02	0.04		
Spelling				0.07	0.46
Constant	97.06	22.73			
Symbols	0.42	0.35	0.21		
Visual search	0.27	1.18	0.04		
Ternus	−0.39	2.52	−0.16		

Note: $^*p<0.05$.

The symbols task measured performance in letter-position encoding, whilst excluding lexical bias. Consistent with previous results, dyslexic readers made fewer correct responses than non-dyslexic readers, suggesting impaired letter-position encoding (Pammer, Lavis, Hansen *et al.*, 2004).

The visual-search task measured visual attention; in the cued conditions, it required efficient dorsal stream functioning (to orient attention to the target position) as well as ventral processing (to discriminate the target orientation). Overall, dyslexic readers made fewer correct responses than non-dyslexic readers, suggesting difficulty in rapid identification of the target and its orientation. Furthermore, performance declined for both the groups as a function of set size, but cued conditions did not facilitate performance relative to uncued conditions for either group. Despite the similarity of our design to other studies' (Baldassi & Burr, 2000; Roach & Hogben, 2004), the non-dyslexic readers in our study did not replicate previous findings of enhanced performance when a cue preceded the target. Although otherwise identical, the cue used in this study yielded a smaller visual angle than in previous studies (approximately 10° compared with 25°), allowing for the possibility that its exogenous cueing potential was reduced.

One explanation for these findings is that the participants' performance may reflect other cognitive processes in addition to impaired dorsal processes in this version of the visual-search task. The rapid visual processing demands in addition to task complexity (combining a visual search with an orientation decision) may tax dyslexic readers' domain-general processing speed capacity (see Wolf & Bowers, 1999, for a review); a possibility we discuss below.

Although cueing did not increase accuracy rates for either group, the significant Cue × Set size interaction suggests that both reading groups were sensitive to the presence of the cue. For both groups, a cue facilitated tilt-orientation judgement when preceding a small number of distracters, but adversely affected performance when preceding a large number of distracters. One possibility is that in this type of visual-search task, involving identification of a tilted target in the presence of vertical distracters, participants employ different search strategies for small as opposed to large set sizes (Pammer, personal communication). In our study, the short presentation time meant that whilst serial search could be employed for smaller set sizes, in larger set sizes, the time limit coupled with the closer spatial juxtaposition of the target with distracters may have prompted a compare-and-contrast search mechanism. When a serial search strategy was employed, the cue may have oriented the participants' attention to the target's location, thus facilitating performance accuracy. Our results suggest, however, that in larger set sizes, the cue information was irrelevant, and at worst interfered with the strategy employed.

Consistent with previous findings, both reading groups in our Ternus task demonstrated a similar pattern of increased 'global' movement judgements in response to longer ISIs (e.g. Cestnick & Coltheart, 1999; Slaghuis et al., 1996). In contrast to Cestnick and Coltheart (1999), however, dyslexic readers did not report fewer global judgements overall relative to non-dyslexic readers. Considering the similarity of our Ternus design to that used by Cestnick and Coltheart, this difference in our results is difficult to interpret. One explanation for the absence of magnocellular deficits often found in dyslexic groups is that the deficit is so mild in these groups that difficulty only arises when magnocellular input is required for the direction of sequential attention (Vidyasagar, 1999). Extending this explanation to the current study, our results suggest that in our high functioning sample, a visual deficit was found only when the task required application of a visual search mechanism. The Ternus did not involve such a mechanism and did not therefore discriminate groups of dyslexic and non-dyslexic readers.

In summary, analyses of group differences show that the adult dyslexic group is impaired relative to non-dyslexic controls on two of the three visual tasks. The symbols task indicates a deficit in letter-position encoding (e.g. Pammer, Lavis, Hansen *et al.*, 2004). In the visual-search task, cued targets did not facilitate accuracy in the non-dyslexic group, rendering interpretation of the overall dyslexic deficit more difficult. The dyslexic deficit may best be interpreted as a cognitive processing-speed or visuo-spatial working memory impairment, but dorsal processes may mediate the sensitivity to cued items demonstrated by both groups. The Ternus task did not discriminate reading groups.

Visual Underpinnings of Letter-position Encoding

Our results suggest that even high-functioning adult dyslexic readers show impaired visual processes. Subsequent analyses examined the predictive relationship between these tasks. Previous research has found no relationship between measures of dorsal function and performance on the symbols task, indexing letter-position encoding (Pammer, Lavis, Hansen *et al.*, 2004). We demonstrate a significant positive correlation between cued performance on the visual-search task and performance on the symbols task. However, visual-search task performance did not contribute significant unique variance to symbols task performance, but the significant correlation suggests that they share a common mechanism. This mechanism may comprise search mechanisms driven by the dorsal stream; consistent with the hypothesis that dorsal functioning plays a role in letter-position encoding by guiding serial attention allocation (Pammer & Vidyasagar, 2005), in addition to its important role in coarse processing of text (Pammer, Lavis, Hansen *et al.*, 2004). However, both tasks may share a common demand for rapid processing speed and visuo-spatial working memory. Future research could further elucidate this relationship between visual attention and letter-position encoding through a more constrained visual-search experiment. The Ternus task does not require a visual search mechanism, which may explain why it did not contribute variance to the symbols task in this experiment.

Contribution of Visual Processing to Reading Component Measures

We next investigated whether the visual tasks map onto components of reading. Performance on symbols and visual-search tasks correlated with non-word reading and rapid automatized naming, reflecting phonological ability and naming speed, respectively. Previous studies indicate a relationship between visual attention (motion sensitivity) and exception word reading (Talcott *et al.*, 2000), but none of our visual tasks contributed significant variance to this reading component. Our finding almost certainly reflects the adult, high-functioning reading population investigated in this study, resulting in possible floor effects: low error counts were found in the exception word task for both groups.

Further analyses regressed performance on the visual-search, symbols and Ternus task against non-word naming, exception word naming, rapid naming and spelling (WRAT-3). Performance on the visual-search task contributed unique variance to non-word naming performance, but no other variables contributed significant unique variance to reading ability. Our results therefore show a relationship between visual attention and phonological decoding. Cestnick and Coltheart (1999) proposed two hypotheses of the way in which visual magnocellular function influences non-word reading. First, the attentional shift required for eye movements may affect the serial processing of letters required for non-word reading. Alternatively, magno cells responsible for processing auditory information might influence phonemic decoding proficiency. Our findings suggest that higher level visual attention processes, potentially controlled by dorsal functioning, affect phonological decoding ability.

Our findings are consistent with the SERIOL reading model (Whitney & Cornelissen, 2005), in which processing letter strings involves making graphemic and phonemic connections between letter items serially. According to this model, each letter receives peak acuity levels across the letter string in turn, firing in a strict left-to-right sequence, and accurate representations of grapheme-to-phoneme correspondence can only be obtained when acuity levels operate in this manner. We suggest that if the dorsal stream is ineffective in guiding attention serially over the letter string, then attention is more dispersed and two or more letter items may be associated with a single phonological label. As a result, phonological codes are ill defined, which is problematic when trying to decode novel or non-words. Furthermore, serial deployment of attention may be particularly pertinent to non-word reading, since whole-word lexical strategies are not available.

Both the visual-search and symbols tasks contributed significant variance to non-word reading, suggesting a common causal link between visual attention, letter-position encoding and phonological decoding: each task reflects a successively 'higher' stage of processing, ranging from perceptual to cognitive domains. However, our results showed that visual attention predicts phonological decoding independently of letter-position encoding. Thus, the evidence suggests that visual attention and letter-position encoding share a common mechanism, but visual attention contributed separately to reading (Pammer, Lavis, Hansen *et al.*, 2004). In this study, however, letter-position encoding did not contribute independent variance to decoding when performance on the visual attention task was controlled, suggesting that the relationship between letter-position encoding and decoding is in part mediated by visual-attention mechanisms.

Performance on both the symbols and visual-search tasks also correlated with rapid automatized naming, despite the fact they did not contribute independent variance to this measure. One potentially important commonality between the two visual tasks and RAN is their emphasis on fast visual processing. Both visual tasks involve short presentation times, requiring rapid visual processing for good performance, suggesting that the rapid visual processing required for successful performance in these tasks is also an important determiner of naming speed. This finding is relevant to the current controversy surrounding the cause of rapid naming deficits in dyslexia, specifically whether slower naming in dyslexic readers reflects impaired covert phonological deficits (Clarke, Hulme, & Snowling, 2005) or has an independent root cause, linked to lower level visuo-attentional and/or timing processes (Wolf & Bowers, 1999). Our results suggest that the ability to rapidly process visual information predicts the speed with which letter items can be named, suggesting that rapid visual processing is a critical factor in naming speed ability.

There was no correlation between performance on the Ternus task and any of the component reading measures, in contrast to previous findings (e.g. Cestnick & Coltheart, 1999; Cornelissen *et al.*, 1998). Taken together with the absence of reading group differences, one interpretation is that for at least these high functioning adults, a visual task that did not include a search mechanism did not distinguish dyslexic readers' performance from non-dyslexic readers.

CONCLUSION

The results of this study suggest robust group differences between adult high-functioning dyslexic readers and non-dyslexic readers: the dyslexic readers are impaired on measures of visual-attention (visual-search task) as well as letter-position encoding (symbols task). Performance on the visual-search task correlated with performance on the symbols task. Furthermore, both symbols and visual-search tasks contributed significant variance to phonological decoding (non-word reading) as well as rapid naming (RAN) components of reading. Our results suggest that visual attention processes are related to component processes of reading, and may comprise an important precursor in the literacy development.

NOTES

1. The only difference between the two analyses was in the symbols task: we found a significant group difference in the symbols task when comparing dyslexic versus non-dyslexic readers (see Results section), but this effect was not significant for 'high' versus 'low' groups in the non-word decoding analysis ($F = 1.9$, $p = 1.7$).

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