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FACULTY OF SOCIAL, HUMAN AND MATHEMATICAL SCIENCES

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Phonological processing during silent reading in children with and without dyslexia

by

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ABSTRACT

FACULTY OF SOCIAL, HUMAN AND MATHEMATICAL SCIENCES

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PHONOLOGICAL PROCESSING DURING SILENT READING IN CHILDREN WITH AND WITHOUT DYSLEXIA

There is a body of evidence to suggest a robust link between phonological processing and the development of reading ability in young readers, and skilled adult readers typically process the speech sounds of words to support lexical identification during silent reading. By contrast, readers with dyslexia have demonstrated impaired performance across a variety of tasks designed to assess phonological processing, and the phonological deficits hypothesis is a widely accepted account of the reading difficulties associated with dyslexia. Despite this, little is known about how young readers with dyslexia cognitively process the speech sounds of words during silent reading, nor how this ability develops in readers either with or without dyslexia. The aim of the present research was to investigate the extent to which readers with dyslexia process the phonological characteristics of words and nonwords during silent reading. Using four participant groups to make chronological age-matched and reading level-matched comparisons, participants' eye movements were recorded as they silent read sentences in which a target word's phonology and orthography was manipulated. In Experiment One foveal processing of phonology was investigated, with parafoveal processing of phonology investigated in Experiment Two. Across both experiments there was no evidence to suggest differential processing of phonology in readers with dyslexia, despite the robust link between dyslexia and phonological processing deficits. There was, however, some evidence to suggest that readers with dyslexia may be more reliant on orthographic processing than typically developing readers. Whilst the sample of readers with dyslexia studied here did demonstrate impairment in some phonological processing tasks, their ability to process phonology during silent reading did not differ from their typically developing peers.

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DECLARATION OF AUTHORSHIP

I, Jonathan H. Dickins, declare that this thesis entitled 'Phonological processing during silent reading in children with and without dyslexia' and the work presented in it are my own and have been generated by me as the result of my own original research.

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;
2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
3. Where I have consulted the published work of others, this is always clearly attributed;
4. Where I have quoted from the work of others, the source is always given. With these exception of such quotations, this thesis is entirely my own work;
5. I have acknowledged all main sources of help;
6. Where the thesis is based on work done by myself or jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
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Chapter One: The acquisition and role of phonological processing in reading and word identification

The speech sounds associated with a word, its phonology, and its written form, its orthography, are inextricably linked. A child undergoing the educational process of learning to read in English must develop their understanding of language in such a way that pre-existing knowledge of spoken sounds is reconciled with a developing ability to represent these sounds through their orthographic forms. Phonological processing refers to the ability to recognise or manipulate the phonological or sound-based characteristics of stimuli for the purpose of the task at hand (e.g., a blending task in which participants are required to combine a series of sounds to form a word). Robust experimental evidence has accumulated to suggest a link between phonological processing deficits and the reading difficulties associated with developmental dyslexia, a reading disability affecting 3-10% of the population (Snowling, 2000).

The first section of this chapter will explore the link between the development of reading ability and phonological processing, and will specifically address the direction of this relationship; whether learning to read is bolstered by phonological processing ability, or whether direct instruction in reading in itself improves phonological processing. The second section of this chapter will serve as a brief introduction to dyslexia, the criteria considered necessary for diagnosis, and will provide an outline of the most influential theories concerning the causes of the reading difficulties associated with dyslexia. The third section will focus upon the role that a word's phonological characteristics play in its lexical identification, with findings from a variety of paradigms discussed.

1.1: Learning to read and the development of phonological processing skills

Phonological awareness and learning to read

A distinction must firstly be made between phonological awareness, the knowledge of, and ability to identify and manipulate, the constituent phonological units of spoken words (Castles & Coltheart, 2004; Wagner & Torgesen, 1987), and other phonological processing abilities. In addition to phonological awareness, Wagner and Torgesen (1987) have identified two other functionally distinct bodies of research into phonological processing. Firstly, phonological memory refers to the ability to store and recall information using sound based representations, and there is evidence to suggest that individual differences in this ability influence reading development (Katz, Shankweiler, & Liberman, 1981; Mann & Liberman, 1984). Secondly, phonological recoding is defined as converting written symbols into a sound-based representational system for lexical access (Wagner & Torgesen, 1987; see also Frost, 1998). The importance of this recoding process during reading will be discussed later in this chapter, and the ability to phonologically recode stimuli has also been shown to predict later reading skill (Jorm, Share, MacLean & Matthews, 1984; Share 1995).

At a very basic level, learning to read can be conceptualised as the development of the ability to extract meaning from print, and achieving this skill is considered a key practical goal for all children as they enter education (Rayner, Foorman, Perfetti, Pesetsky, & Seidenberg, 2001). The fact that learning to read requires extensive instruction reflects the inherent difficulty of deciphering the mappings between phonology and orthography (Foorman, Francis, Fletcher, Schatschneider, & Mehta, 1998; Gough & Hillinger, 1980; Liberman, 1992). The nature of these mappings varies by language, with English having an ‘opaque’ relationship between the orthographic and phonological forms of words (Ehri, 2005, p. 185). A full review of reading development in other languages is outside of the scope of this review, but it has been demonstrated that the progress children make in learning to read is accelerated in languages such as German or Finnish (Aro & Wimmer, 2003; Cossu, 1999; Katz & Frost, 1992; Patel, Snowling, & de Jong, 2004, Ziegler & Goswami, 2005), where the relationship between phonology and orthography is more consistent. These cross-linguistic differences suggest that the ability to understand these mappings, and the inconsistencies they introduce, is important for an emergent reader.

Children experience speech extensively prior to learning to read, and the experimental literature demonstrates that phonological awareness is typically present in pre-readers. Despite using a small sample, Fox and Routh (1975) found that some children could segment syllables into phonemes at age three (see also, Liberman, Shankweiler, Fischer, & Carter, 1974), and children tested at age four were able to perform above chance on rhyme detection tasks (Lenel & Cantor, 1981; MacLean, Bryant, & Bradley, 1987). Phonological processing skills have also been shown to increase with age in pre-school children (Lonigan, Burgess, Anthony, & Barker, 1998). Lonigan et al. (1998) measured the phonological processing skills of children aged two, three, four, and five years of age, finding significant age-related increases in performance between all groups on an elision task (requiring the participant to subtract a phoneme from a word) and a blending task (requiring the participant to combine phonemes). Whilst performance within the youngest age groups was poor on the rhyme task, with only around one third of participants performing above chance, there was evidence to suggest that very young children were capable of blending and elision at a syllable and phoneme level. These studies suggest that young children are able to identify and manipulate phonological units of words prior to direct instruction in reading. Early phonological awareness allows developing readers to recognise the link between sounds and letters, a process considered important in the acquisition of reading (see Liberman, Shankweiler, & Liberman, 1990). The extent to which pre-existing phonological awareness impacts on reading development is discussed in the following paragraphs. Two particular experimental designs have been particularly informative with regards to this issue: Longitudinal correlational studies, and experimental training studies.

Firstly, longitudinal designs will be discussed, which typically involve measuring phonological awareness at one point, and correlating this performance with reading ability at a second point in the future. Statistical modelling techniques can then be employed to test alternative hypotheses regarding the link between phonological awareness and reading ability (Wagner & Torgesen, 1987). Wagner and colleagues (Wagner, Torgesen, & Rashotte, 1994; Wagner et al., 1997) have presented two such studies following a large sample of young readers from kindergarten to fourth grade, assessing them once per year with a large battery of phonological and reading-related tasks. Reporting analyses conducted after 2 years, Wagner et al. (1994) firstly found that individual differences in phonological processing abilities, including phonological awareness, were extremely robust over the studied time period. This finding suggests that phonological awareness is a stable construct that can be measured consistently over time. Secondly, Wagner et al. (1994) reported that their results supported the hypothesis of a bidirectional relationship between phonological awareness and learning to read. All of their measured phonological variables predicted later decoding ability (as measured by a nonword reading task), and whilst decoding ability was not found to be a predictor of later phonological awareness, letter-name knowledge was (see also, Burgess & Lonigan, 1998). Reporting after five assessments, Wagner et al. (1997) found that between kindergarten and first grade, phonological awareness predicted 23%

of the variance in later word reading. Between first and third grade, this figure was 8%, and between second and fourth, 4%. The decline in the proportion of variance explained by phonological awareness was attributed by the authors to an increase in variance explained by factors such as developments in vocabulary. Wagner et al. (1997) suggested that phonological awareness offers a small but statistically significant influence on later reading ability.

Similar results have also been reported from other longitudinal investigations. Mann and Liberman (1984) reported that phonological awareness at kindergarten level, as measured by a syllable-tapping task, was significantly correlated with later reading abilities (though see Badian, 1988), and Mann (1984) demonstrated that kindergarten performance on a phoneme reversal task was very highly correlated with first-grade reading ability. MacLean et al. (1987) found that children at age three demonstrated above chance performance in rhyming tasks, and that rhyming skill at age three correlated with single word reading ability at age four. Bryant, MacLean, Bradley, and Crossland (1990), following the sample of children tested by MacLean et al. (1987), observed that there was a significant relationship between rhyming skills at age three and spelling ability at ages five and six, even after controlling for IQ. Similarly, a more recent study by Muter, Hulme, Snowling, and Stevenson (2004) found that phoneme sensitivity at five years of age was a significant predictor of later word recognition skills. These studies provide very strong evidence for the existence of a causal relationship between phonological awareness and success in learning to read. It must, however, be noted that the correlational nature of these designs does not exclude the possibility that an unknown third variable may affect this relationship (Castles & Coltheart, 2004)

If this relationship is causal in nature, explicit training in phonological awareness should boost reading ability, even prior to direct reading instruction. Training studies are often used to assess the impact of explicit phonological awareness training on later reading ability. Such studies typically involve enrolling participants in a specific programme of training in phonological awareness, and later reading performance is then compared with that of a control group who did not receive training (Bus & Van Ijzendoorn, 1999). Analysing 34 phonological awareness training studies, Bus and Van Ijzendoorn (1999) found that phonological awareness training not only improved overall phonological awareness itself, but also reading ability in general, albeit finding a smaller effect size for the improvement in reading ability. Bus and Van Ijzendoorn (1999) concluded that phonological awareness is a consistent and causal predictor of reading ability. Another meta-analysis specifically evaluating the effects of phonemic awareness training on learning to read was conducted by the National Reading Panel in the United States of America, and was reported by Ehri, Nunes, Stahl et al. (2001; see also Ehri, Nunes, Stahl, & Willows, 2001). This meta-analysis focused on phoneme awareness training, as opposed to training in larger phonological units such as syllables. Across 52 studies, phonemic awareness training exerted a moderate and statistically significant impact on reading ability for a number of groups; typically developing readers, disabled readers, and low socioeconomic status readers all benefited significantly (see also, Bowyer-Crane et al., 2007). The evidence presented thus far from longitudinal and training studies strongly supports a causal role for phonological awareness in learning to read. As mentioned, however, the link between phonological awareness and later reading ability can be interpreted in multiple ways.

Issues around the nature of causality invariably arise when empirical proof of a relationship between two factors is investigated (Castles & Coltheart, 2004; Goswami

& Bryant, 1990). Understanding the nature of the relationship between phonological awareness and the acquisition of reading skill is particularly important, as if it is indeed the case that phonological awareness does underpin learning to read, any difficulties that arise in phonological awareness will impact upon reading development. There is now a great deal of evidence linking phonological processing abilities with reading skill (for reviews, see Castles & Coltheart, 2004; Wagner & Torgesen, 1987), but, as mentioned above, there are a number of ways to theoretically interpret this relationship. The dominant view, as discussed in the previous paragraph and evidenced by a range of longitudinal and training studies, is that phonological processing skills represent a causal factor in the development of reading ability. It may also be the case, however, that the relationship is bidirectional, and not only that phonological processing skills impact learning, but that the development of orthographic knowledge in turn facilitates some or all phonological processing abilities (see Wagner et al., 1994).

One of the earliest studies to examine this relationship demonstrated that children's phonological awareness markedly improved at the age at which they began to read. Liberman et al. (1974) used a tapping task, requiring children to tap once for words with one syllable or phoneme, twice for words with two syllables or phonemes, and three times for words with three syllables or phonemes. Liberman et al. (1974) found that among four-year-old children, none could identify the number of phonemes in a word, whilst half could identify the number of syllables. At age five, 17% were able to count phonemes, and half were able to count syllables, and by age six, 70% of children were able to determine the number of phonemes in a word, and 90% were able to count syllables. It would appear that syllable awareness may predate explicit instruction in reading. Further evidence for this assertion has been demonstrated by studies sampling illiterate participants, some of which are discussed below. This suggests that the process of learning to read may in turn boost phonological awareness, and in particular awareness of phonemes.

If phonological awareness develops in tandem with learning to read, then some differences between illiterate and literate adults may be expected, as the former have not received explicit reading instruction. Morais, Cary, Alegria, and Bertelson (1979) examined the phonological processing abilities of illiterate adults and compared them to formerly illiterate adults currently enrolled in adult literacy programmes, using elision, blending, and sound reversal tasks (e.g., reversing the order of syllables in a word). The illiterate subjects were particularly poor at manipulating phonemes of nonwords, and 50% of illiterate subjects failed on every nonword trial. Literate adults averaged 91% and 87% on addition and deletion tasks respectively, with illiterate subjects scoring 46% and 26% on each task. This lack of phonological processing ability suggests that this skill does not develop in isolation, and Morais et al. (1979) posited that the process of learning to read allows phoneme awareness to develop and manifest itself (see also Reis & Castro-Caldas, 1997). This study, however, did not account for other potential differences between participant groups (Goswami & Bryant, 1990), and nor did Morais et al. (1979) test participants on phonological units other than phonemes, such as syllables. More recent studies have attempted to control for potential differences between participants more carefully.

Qualitatively different reading patterns have been observed in adults receiving literacy instruction and reading-age matched children. Greenberg, Ehri, and Perrin (2002) used an error analysis technique to examine the nature of the errors made by adult literacy students and children at the equivalent reading level. Using data collected by Greenberg, Ehri, and Perrin (1997), Greenberg et al. (2002) found that adults were more likely to apply orthographic knowledge when making a mistake. For instance, on a sight word reading test, where participants were required to pronounce an irregular word, adult literacy participants were more likely to misread an item as a similarly spelled word (e.g., reading aloud *machine* for the item *mechanic*), whereas reading-age matched children were more likely to make phonological errors (e.g., stating *dentee* for *deny*). The adult group were also significantly more likely to read nonwords as real words, and more likely to produce non-phonetic errors in a spelling task, demonstrating an overreliance on orthographic strategies and a difficulty in applying grapheme-phoneme rules (see also, Siegel, Share, & Geva, 1995). These studies suggest that a lack of early reading instruction may lead to a reading strategy that is over-reliant on orthographic knowledge, and a difficulty in applying phonological awareness. Taken together alongside longitudinal studies (Wagner et al., 1994), which have clearly demonstrated a link between learning to read and the improvement of phonological awareness, there is clearly evidence of a bidirectional relationship between the development of phonological awareness and reading ability.

It has been suggested, however, that the wide variety of tasks used to assess phonological processing abilities at the kindergarten stage has made the drawing of an unequivocal conclusion on the nature of the relationship between phonological processing and learning to read more difficult. Stanovich, Cunningham, and Cramer (1984) pointed out that the lack of more direct comparison between tasks renders consolidation of the knowledge gained more difficult. Conducting ten different phonological processing tasks, Stanovich et al. (1984) found that performance between tasks was generally highly correlated, however, suggesting that these measures essentially tapped the same phonological abilities without an apparent influence of differing cognitive demands.

In summary, is has been robustly demonstrated from a variety of longitudinal studies that there is a link between phonological awareness and reading ability (Castles & Coltheart, 2004; Mann, 1984; Mann & Liberman, 1987; Wagner & Torgesen, 1987; Wagner et al., 1994), and more specifically that awareness of phonology is a causal factor in later reading success. Moreover, phonological awareness training facilitates reading development in children who are learning to read. Further investigation of this link has revealed the relationship may be bidirectional, in that learning to read in itself boosts phonological awareness. With this robust link in mind, various theories will now be discussed, with the focus upon how each theory considers phonological awareness.

Theories of reading development

Whilst there is agreement over the importance of phonological processing skills in learning to read, disagreements over precisely how learning to read should be conceptualised have arisen. Many early theories focused upon the assumption that children pass through unique and distinct stages from beginning to skilled reading (e.g., Frith, 1985; Marsh, Friedman, Welsh, & Desberg, 1981). From a practical standpoint this is an attractive assumption, as it potentially allows educators to monitor and support developing readers in accordance with these stages (Beech, 2005). Stage theories impose a conceptually rigid progression in reading ability; a stage cannot be skipped, and stages are represented in a fixed order. In each stage, a developing reader adds a new skill or implements a new strategy that supports reading.

One early stage model for reading development was put forward by Frith (1985). According to this model, children progress through three main stages: a logographic stage, an alphabetic stage, and an orthographic stage. Initially, words are read as logograms, with children identifying letter sequences. This was supported by Seymour and Elder (1986), who taught young beginner readers lists of new words, and subsequently tested their reading. They found that the majority of errors were visual in nature (e.g., confusing words based on their length, or those with salient features in common, such as sharing the medial consonant cluster in '*smaller'* and '*yellow'*). This suggests that reading at a very early stage depends to some extent on visual memory, but while this is sufficient for simply recognising a limited set of words, as vocabulary expands this strategy becomes unsustainable due to exposure to similarly spelled words. Spelling ability requires a different set of skills that become apparent in the next stage, the alphabetic stage (Snowling, 2000). In this stage, children begin to apply their developing knowledge of the relationship between graphemes and phonemes to reading, and Frith suggested that they begin to engage in phonological decoding strategies, which help them to identify words not previously encountered in print. Finally, in the orthographic stage, children apply not only grapheme-phoneme knowledge, but knowledge of the morphological characteristics of words.

Stage theories in this area are ambitious in their attempts to track reading development, but are ultimately poorly specified (Snowling, 2000), particularly when considering the potential cognitive mechanisms for progression from one stage to the next; these are often undefined. Their universality has also been questioned; evidence suggests the development of reading strategies depends on factors such as teaching technique (Johnston & Thompson, 1989), and the language in which the child is learning (Wimmer & Hummer, 1990). Such variance is not accounted for by the more rigid design of stage theories.

Phase theories eschew the strict criteria associated with stage theories; each phase is not necessarily a pre-requisite of the next (Ehri, 2005). Instead of a strategy or skill being exclusively used within one stage, phase theories conceptualise each phase as a period of time in which one strategy or skill is dominant over others. This does not forbid the on-going use of other strategies or skills associated with different phases. A prominent example of a recent phase theory is that of Ehri (1980, 1991), who posited a series of alphabetic phases. Initially to a beginner reader, letter-sound correspondences are not explicitly known; this is the termed the pre-alphabetic phase. Somewhat similar to Frith’s (1985) logographic stage, this stage is characterised by an initial reliance on the visual features of words for identification, and children begin to learn the names and sounds of letters as they progress into the partial alphabetic phase. Words often seem to be identified by first and last letters; Savage, Stuart, and Hill (2001) found that early readers would often confuse words such as ‘skin’ and ‘spoon’, which shared initial and final letters. A more complete connection between letters and their sounds signals the full alphabetic phase, and knowledge of basic grapheme-phoneme correspondences becomes evident (see Ehri & Wilce, 1987). In the final phase, the consolidated alphabetic phase, children achieve knowledge of rimes, syllables and morphemes. There are no operational definitions for how a child could ordinarily be expected to progress from one phase to another, and Beech (2005) has suggested that this theory serves more as a framework than a set of falsifiable hypotheses.

Goswami and Bryant (1990) have developed a theory that avoids the implementation of stages or phases, and instead focuses on connections between skills that drive the acquisition of reading ability. The causal connections theory (Goswami & Bryant, 1990; Goswami, 1999) postulated three such links: firstly, a connection between awareness of rhyme as measured in pre-readers and later progress in reading; secondly, between explicit phoneme tuition and phoneme awareness; finally, a connection between progress in spelling and progress in reading. The first two connections are linked, in that rhyming ability can predict a child’s ability to detect phonemes, but these two connections make independent contributions to reading ability. A child's ability to use their knowledge of rhyme to categorise words means that analogy can be used to generalise existing knowledge to new words. Rhyming ability is conceptualised as a skill that develops prior to learning to read, as evidenced by the studies described above that show that pre-readers are sensitive to rhyme. It is only as children receive explicit instruction in the nature of phonemes that they develop phonemic awareness. The final connection concerns the relationship between reading and spelling. Goswami and Bryant (1990) suggested that, while these two skills are quite distinct at first, they begin to exert an influence on each other as the child continues to learn to read. The authors admit, however, that this final connection is speculative and unspecified. The notion of the first two causal connections argued by Goswami and Bryant (1990) are well evidenced by the longitudinal studies previously discussed, which have suggested not only that phonological awareness in pre-readers is a significant predictor of later reading ability, but that the process of learning to read improves phonological processing skills (Wagner et al., 1994).

Finally, a more recent theory has focused more explicitly upon the development of phonological awareness, and in particular the acquisition of awareness of different phonological units, to explain the process of learning to read. Phonological awareness can be thought of as the awareness of and the ability to manipulate different sized phonological units (e.g. syllables, onset-rimes, phonemes), and according to the psycholinguistic grain size theory (Ziegler & Goswami, 2005), awareness is assumed to progress from knowledge of larger units such as syllables, through intra-syllabic units, to phonemic awareness. In order to learn to read, children must become aware of different grain sizes that allow an efficient mapping between orthography and phonology (Ziegler & Goswami, 2005). For instance, syllables are comprised of onsets and rimes. The term onset refers to the consonant or consonant cluster prior to the first vowel (e.g., *st* in *stack*), whilst the first vowel and subsequent letters (e.g., *ack* in *stack*) are referred to as the rime. Each syllable is also comprised of phonemes, the perceptually distinct units of sound that differentiate words from one another. Given the variety of phonological units that a reader may progressively become aware of, a number of studies have investigated the order with which young readers develop an awareness of these units.

Evidence for an awareness of larger units, such as onsets and rimes, prior to phoneme awareness has been provided by the oddity task (Bradley & Bryant, 1978). In this task, participants are required to select which of three visually presented words is the 'odd one out' based on lacking a sound shared by the other two words. Crucially, however, recognising that words share the same final sound means bisecting the rime unit, and if indeed children are sensitive to these units, performance should be better on initial sound items (e.g., *steak, steel, frame*) than final sound items (e.g., *steak*, *steel*, *wheel*). This has indeed been the case (Kirtley, Bryant, MacLean, & Bradley, 1989, though see MacMillan, 2002), suggesting that breaking up rime units to isolate phonemes is detrimental to performance in young readers. More recent work has adopted sophisticated statistical techniques to investigate the development of sensitivity to different phonological units. Anthony, Lonigan, Driscoll, Phillips, and Burgess (2003) collected data from almost 1000 children, between the ages of two and six, employing hierarchical loglinear and confirmatory factor analyses to allow a model to be developed describing how sensitivity to different sized units develops. Children were initially screened to ensure typically developing speech and language abilities, and their phonological awareness was measured at various grain sizes. It was found that children demonstrated awareness of syllables first, followed by intra-syllabic units such as onsets and rimes, and finally awareness of phonemes (see also, Carroll, Snowling, Hulme, & Stevenson, 2003). These studies demonstrate that phonological awareness at different grain sizes emerges from large to small units.

Whether theorists conceptualise reading development as the addition of new skills or strategies in stages and phases, or through a less rigid design, they agree on a significant role for phonological processing. The stage/phase theories discussed largely focus on the transition between periods where one strategy or skill is used or is dominant, but each considers phonological processing a necessary tool for learning to read successfully. Theories from Goswami and Bryant (1990) and Ziegler and Goswami (2005) do not represent the process of learning to read in distinct stages, but each focuses upon the importance of phonological awareness in learning to read.

In summary, this section has robustly demonstrated the bidirectional link between phonological awareness and learning to read. Early phonological awareness is a significant predictor of later reading ability, and the process of learning to read serves to improve phonological awareness. These very consistent findings have informed the development of several models of learning to read, and theoretical positions placing phonological awareness at the forefront have been outlined. With this link in mind, the next section will focus upon developmental dyslexia, a specific reading disability, widely assumed to originate from deficits in phonological awareness.

1.2: Developmental dyslexia

The previous section of this chapter established the link between learning to read and phonological processing, considering evidence that strongly suggests phonological processing abilities are an important factor in the acquisition of reading skill. In many cases, however, a child’s reading ability does not develop in accordance with that of their peers, despite very similar instruction and no disadvantages in terms of intelligence. This specific pattern of reading difficulty is termed dyslexia, and there is compelling evidence that developing readers with dyslexia are impaired in measures of their phonological processing ability. The most recent iteration of The Diagnostical and Statistical Manual of Mental Disorders (5th ed.; DSM-V, American Psychiatric Association, 2013) criteria for the diagnosis of specific learning disorder (with difficulties in reading) state that an individual must demonstrate "difficulties learning and using academic skills as indicated by the presence of…inaccurate or slow and effortful word reading.". Dyslexia is specifically defined as "a pattern of learning difficulties characterized by problems with accurate or fluent word recognition, poor decoding, and poor spelling abilities.". As described later in this section, dyslexia has been very robustly linked with phonological processing difficulties, and the omission of this link from the DSM-V criteria has been criticised (Snowling & Hulme, 2012). It is also important to note that reading comprehension among individuals in dyslexia is typically intact (Peterson & Pennington, 2012), with problems largely arising in word reading.

In academic terms, a vast amount of time has passed since a case of dyslexia was first described by Morgan (1896), and a far greater understanding of the cognitive processes involved in reading has developed in the intervening years. Despite these advances, however, dyslexia remains a greatly debated subject, both in terms of how it should be diagnosed and its underlying causes. These issues will be addressed in this section.

Diagnosis and genetic basis

Rutter and Yule (1975) were among the first to make the distinction between 'reading backwardness', the observation that a child is reading at a lower level than peers of the same age, and 'reading retardation', the observation of specific reading disability not explicable by lower intelligence. It is the latter group that were usually considered to be the ‘dyslexic’ group, with the notion of an ‘IQ discrepancy’ in dyslexia gaining support (Ellis, McDougall, & Monk, 1996; Snowling, 1998; though see Stanovich, 2005). A correlational approach can then be used to compare reading-disabled and typically developing children; if a child demonstrates reading ability significantly below that predicted from their intelligence, on the basis of the correlation between reading and IQ in other children, there may be a specific reading disability. There is, however, evidence to suggest that the phonological deficit widely hypothesised to be present in dyslexia is in evidence among readers of both high and low IQ (Stuebing et al., 2002; Tanaka et al., 2011, see Stanovich, 2005), leading some to reject the traditional IQ discrepancy definition of dyslexia. In contrast to the previous version of the DSM (4^{th} ed.; DSM-IV, American Psychiatric Association, 1994), the most recent version (5^{th} ed.; DSM-V, American Psychiatric Association, 2011) has removed all mention of IQ from its diagnostic procedure for specific learning disorder, under which dyslexia is subsumed.

That there is a genetic basis for dyslexia is now well established in the literature; higher risk of dyslexia is observed in children with a parent with dyslexia in studies of concordance rates (DeFries, Fulker, & LaBuda, 1987). These types of studies are particularly useful in decoupling the influence of a genetic component and that of a child’s environment and familial studies, with Vogler, DeFries, and Decker (1985) finding that the risk to a son having a father with dyslexia was 40%, and from having a mother with dyslexia was 35% (see also, Rutter & Yule, 1975). The probability of sibling recurrence is estimated as 43-60% (Volger et al., 1985), and concordance rates are higher in monozygotic twins than in dizygotic twins (Snowling, 2000). Given that the overall population risk is substantially lower, as cited above, there does indeed appear to be some genetic basis for dyslexia. Snowling (1998) suggests that aspects of language processing, rather than reading disability per se, are inherited, and the search for a specific ‘dyslexic gene’ may be fruitless as the process of reading requires the utilisation of a number of disparate cognitive abilities, such as word identification, orthographic coding, and oculomotor control. Some potential susceptibility genes have, however, been highlighted (Francks et al., 2004; Cope et al., 2005; see Williams & O’Donovan, 2006; Giraud & Ramus, 2013 for reviews). Moreover, some neurobiological abnormalities have been linked to dyslexia, some of which will be covered in later in this section in relation to theories around dyslexia (for reviews, see Lyon, Shaywitz, & Shaywitz, 2003; Raschle, Chang, & Gaab, 2010).

Dyslexia is notable for its heterogeneity; the associated reading difficulties are not entirely uniform across individuals with dyslexia (Castles, Datta, Gayan, & Olsen, 1999; Ramus et al., 2003). The issue of whether individuals with dyslexia can be categorised into distinct subtypes is prevalent in the literature (Bodor, 1973; Fletcher & Morris, 1986; Stanovich, Seigel, & Gottardo, 1997), with phonological dyslexia and surface dyslexia identified as two potential subtypes. Phonological dyslexia is characterised by difficulties in nonword reading but relatively preserved reading ability on irregular words (words that do not conform to grapheme-phoneme correspondence rules, e.g., *sausage*). This is indicative of an overreliance on word specific knowledge, and a deficit in applying grapheme-phoneme rules. Conversely, surface dyslexia is associated with the opposite pattern- no deficit in nonword reading but impairments in reading irregular words, demonstrating an overreliance on grapheme-phoneme rules, which cannot be used to name irregular words. These distinct patterns were first identified in individual case studies of acquired dyslexia (reading difficulties emerging as a result of brain injury or disease; Coltheart, Masterson, Byng, Prior, & Riddoch, 1983; Temple & Marshall, 1983), and the extent to which individuals with developmental dyslexia can be categorised in this way has been subsequently investigated.

Importantly, a number of studies have since found that at least half of individuals with developmental dyslexia exhibit a ‘mixed’ reading profile, showing reading impairments on both nonwords and irregular words, rather than a clear dissociation between these two types of stimuli (Castles & Coltheart, 1993; Manis, Seidenberg, Doi, McBride-Chang, & Peterson, 1996; Peterson, Pennington, & Olson, 2013; Stanovich et al., 1997). Studies using a reading-age matched comparison (comparing individuals with dyslexia to younger readers with equivalent word reading skill) have found that those classified as surface dyslexics are no poorer in terms of reading ability than their reading-matched peers (Manis et al., 1996; Stanovich et al., 1997, Sprenger-Charolles, Cole, Lacert, & Serniclaes, 2000), suggesting that surface dyslexia may represent a developmental delay rather than a developmental deficit. Whilst there may not be sufficient evidence to conclude that dyslexia has specific subtypes, it has nonetheless been found that readers with dyslexia display a varying pattern of difficulties (Ramus et al., 2003).

In summary, dyslexia is a specific reading disability, affecting abilities in fluent word and nonword reading and decoding. Arguments within the literature, however, surrounding the importance of IQ (Rule & Yutter, 1975; Stuebing et al., 2002; Tanaka et al., 2011) and the ‘mixed’ reading profiles typifying the heterogeneous nature of dyslexia (Castles & Coltheart, 1993; Manis et al., 1996; Peterson et al., 2013; Stanovich et al., 1997) have made the development of a unanimous definition difficult. This has not only impacted the changing diagnostic criteria of dyslexia, but also the theoretical attempts to understand the causes of the reading difficulties associated with it. As outlined in the next subsection, there are a variety of prevalent theories for the causes of dyslexia.

Phonological deficits

As discussed at length in previous subsections, there is a clear link between phonological processing skills and learning to read. There is also abundant experimental evidence that readers with dyslexia are impeded on tasks requiring phonological processing. Children with dyslexia perform at a significantly poorer level than their peers in various phonological tasks, such as selecting the ‘odd one out’ from a series of items, all but one of which share sounds in common (Bradley & Bryant, 1978), multisyllabic nonword repetition tasks (Snowling, 1981), and short-term verbal memory tasks (Hulme, 1981). Participants with dyslexia often confuse similar words, e.g., ‘pacific’ for ‘specific’ (Snowling, 2000) and show greater difficulties in labelling objects, particularly if the name is low frequency or polysyllabic (Katz, 1986) and on naming-to-definition tasks (Murphy & Pollatsek, 1994). Naming tasks have been useful in attempting to investigate the basis of a proposed phonological deficit, and participants with dyslexia have demonstrated difficulties retrieving phonological information from memory. Snowling, van Wagtendonk, and Stafford (1988) measured the ability of children with dyslexia in two naming tasks; in the first, participants were required to match a name of an object to a picture, and in the second they were asked to provide a name themselves. The first task was purely semantic, and children with dyslexia performed no worse than reading-age controls (younger participants matched for reading ability). The second task required the recruitment of phonological memory, and it was in this task that children with dyslexia were significantly impaired, suggesting well specified semantic representations, but poorly specified phonological representation (Snowling, 2000). The research discussed previously in this chapter, linking phonological processing skills with reading ability and the prevalence of these deficits in readers with dyslexia, has given rise to a phonological deficit hypothesis for dyslexia (e.g., Liberman, 1973; Vellutino, 1979; Snowling, 1981; Stanovich, 1988). According to this theory, a specific deficit with regard to storage and retrieval of speech sounds is posited to be the key causal factor leading to the reading difficulties associated with dyslexia. This deficit hinders the learning of grapheme-phoneme correspondences, a skill considered to be one of the foundations for the development of reading ability (Ramus et al., 2003). This lack of specification leads to less fully specified cognitive representations of words for readers with dyslexia.

Three aspects of the phonological deficit have been posited by Ramus and Szenkovits (2008) Firstly, a phonological awareness deficit is evidenced by impaired performance on tasks requiring the manipulation of speech sounds, such as the ‘odd one out’ task (Bradley & Bryant, 1978). Secondly, a deficit in verbal short term memory (Hulme, 1980), suggesting that their ability to hold the phonological forms of words in memory may be impaired. Finally, slower lexical retrieval impairments are shown through poorer performance in rapid automatized naming tasks (Denckla & Rudel, 1976; Branigan, Kelly, & Jones, 2009). A number of more recent explanations of how these phonological deficits affect reading development have been put forward. For instance, Ramus and Szenkovits (2008) have suggested that the cognitive representations of readers with dyslexia are intact, but that access to these representations is hindered as a function of certain tasks (see also, Ramus & Szenkovits, 2008; Szenkovits, Darma, Darcy, & Ramus, 2016).

While most researchers do not specifically refute the presence of phonological deficits in dyslexia, many who challenge the phonological deficits hypothesis have suggested that dyslexia has its roots in sensory or motor dysfunctions. The phonological deficits hypothesis suggests that sensory or motor disorders observed in dyslexia are not core features of the disorder, but others have argued their significance. Proponents of alternative theories have suggested that deficits in the magnocellular pathway (Stein, 2001) or the cerebellum (Nicolson, Fawcett, & Dean, 2001) are potential causes of dyslexia. Such theorists see the phonological deficits observed in dyslexia as a marker for the condition, but view dyslexia as a more extended disorder, having roots in sensory, motor or learning processes, and that a phonological processing deficit is an aspect or consequence of a more general reading disorder (Ramus, 2003).

Cerebellar deficits

The cerebellar theory has developed from the observation of a number of motor impairments in children with dyslexia (Denckla, 1985; Wolff, Cohen, & Drake, 1984). The cerebellum is traditionally considered an area of the brain responsible for motor control, and damage to this area, depending on exact location, affects guidance of movement and motor skills (Ivry & Fiez, 2000; Stein & Glickstein, 1992). Leiner, Leiner, and Dow (1993) suggested that some cognitive and linguistic functions may be cerebellar (for reviews of language functions, see De Smet, Baillieux, De Deyn, Mariën, & Paquier, 2007; Murdoch, 2010). With specific regard to reading, the cerebellum is active in silent reading and language processing (for reviews, see Fabbro, 2000; Ackermann, 2008) and visual motor activities such as eye movements (Stein & Glickstein, 1992). There is also evidence for acquired reading difficulties in patients with cerebellar damage, which can trigger a ‘knock-on effect’ on reading (Stoodley & Stein, 2013) including impaired development of verbal and literacy skills in children (Scott et al., 2001) and impaired reading performance in adults (Karacı, Öztürk, Özbakır, & Cansaran, 2008). The exact role of the cerebellum in higher cognitive function is, however, still not entirely determined (Beaton & Mariën, 2010; Stoodley & Stein, 2011).

Nicolson and Fawcett (1990) investigated multitasking in children with dyslexia compared to chronological age- matched control subjects. When subjects were completing a single task, such as an examination of motor balance, there was no difference between the dyslexia group and the control group. When a secondary task, such as counting backwards, was employed at the same time, however, children with dyslexia were significantly impaired and performance was worsened on the original balancing task. Nicolson and Fawcett (1990) suggested that this represents a failure of automaticity in dyslexia- a need for 'conscious compensation' even in simple motor or cognitive tasks that typically developing children need not allocate such resources to. A study by Nicolson, Fawcett and Dean (1995) also found that participants with dyslexia demonstrated poorer performance on a time-estimation task, a non-motor task assumed to tap cerebellar function.

These findings form the basis of the cerebellar deficit hypothesis, with Nicolson, Fawcett and colleagues noting that children with dyslexia have problems almost universally with balance (Nicolson & Fawcett, 1990), motor skill (Fawcett & Nicolson 1995), and rapid processing (Fawcett & Nicolson, 1994), due to minor overall dysfunction in the cerebellum. Nicolson, Fawcett, and Dean (2001) reported a positron emission topography (PET) study undertaken on typically developing participants and participants with dyslexia, testing cerebellar function in a non-reading domain using a trial and error learning task. They found significantly less activation in the right hemisphere of the cerebellum in participants with dyslexia, and suggested this abnormal function is a definitive cause of dyslexia. Neuroimaging studies have demonstrated that typically developed readers tend to show more right-lateralised cerebellar asymmetry, whereas readers with dyslexia have more symmetrical cerebella (Rae, et al., 2002; Kibby, Fancher, Markanen, & Hynd, 2008). Moreover, these studies reported that cerebellar symmetry correlates with phonological processing difficulties. This symmetry, however, may simply lead to wider cognitive deficits, and may not be unique to dyslexia (Leonard, et al., 2008). The issue of causality is vital to the efficacy of any theory targeting the causes of dyslexia, as discussed in the next paragraph.

Bishop (2002) suggested that it is too simplistic to imply cause and effect from such findings, and that the deficits observed in such motor tasks as described above may simply represent an overall deficit in fine motor skill. Writing is among the most precise of motor skills, and children with reading difficulties are likely to be less practiced than their typically developing peers. A lack of practice here may lead to a universal motor deficit that is a consequence and not a cause of dyslexia. Bishop (2002) also argued that a number of structural and functional differences have been discovered in the brains of those with dyslexia, not just localised within the cerebellum. It may simply be that cerebellar dysfunction is a correlate of dyslexia, and considering the immense plasticity of the cerebellum itself, it is difficult to identify where exactly a disruption first begins.

A number of studies have also failed to replicate important theoretical findings. Results have been mixed in attempts to replicate Nicolson and Fawcett's dual tasks involving balance (Wimmer, Mayringer, & Landerl, 1998; Yap & van der Leij, 1994), and Ramus, Pidgeon, and Frith (2003) have found smaller effect sizes than those reported by Fawcett and Nicolson (1996). Moreover, whilst the cerebellar deficit hypothesis links motor difficulties with reading difficulties, not all participants with dyslexia show this pattern of symptoms. White et al. (2006) found that whilst all children with dyslexia in their sample showed phonological impairments, the group did not show significant difficulties in sensorimotor tasks. Conversely, many with dyslexia show dysfunctions not fully accounted for by a purely phonological deficit, as discussed by the magnocellular account below.

Magnocellular deficits

Whilst reading printed text, information reaches the visual cortex via two separate pathways from the retina- the magnocellular (M) and parvocellular pathways via the lateral geniculate nucleus (LGN). It has been found that children with dyslexia often transpose letters (for example, confusing the letters *b* and *d*, Vidyasagar & Pammer, 2009), show difficulties reading with small print sizes (Cornelissen, Bradley, Fowler, & Stein, 1991), and display consistent motor difficulties and poor balance (Nicolson & Fawcett, 1995). Early theories into the potential visual causes of dyslexia focused on such problems and attempted to frame dyslexia as a visual processing deficit (Lovegrove, Bowling, Badcock, & Blackwood, 1980; Livingstone, Rosen, Drislane, & Galaburda, 1991) with its roots in a selective disruption to the M pathway. The M pathway begins with retinal ganglion cells, and terminates in the primary visual cortex, via the LGN. Convergent evidence from anatomical studies showing magnocellular abnormalities in the LGN (Livingstone, et al., 1991), psychophysical studies on sensitivity to spatial and temporal frequencies in dyslexia (Lovegrove et al., 1980), and brain imaging studies (Eden et al., 1996) indicated the existence of magnocellular dysfunction in some individuals with dyslexia (Galaburda & Livingstone, 1993). This theory does not refute the presence of phonological deficits, but proposes a significant role for visual contributions to reading problems (Ramus, et al., 2003). Stein and colleagues (Stein & Walsh, 1997; Stein, 2001) extended this theory, implicating other modalities such as touch and audition in addition to visual deficits, whilst noting the significant input of the magnocellular pathway into the cerebellum. In this way, the magnocellular theory can be said to be an integration of empirical findings discussed above in relation to the various hypotheses of dyslexia (Ramus et al., 2013). This integration is supported by the co-occurrence of visual and auditory problems in some participants with dyslexia (Cestnick, 2001), and the observation of smaller magnocellular layers within the LGN in participants with dyslexia (Galaburda, Sherman, Rosen, Aboitiz, & Geschwind, 1985). Phonological processing deficits are largely explained by deficiencies in auditory and visual abilities that independently contribute to such a deficit (Stein, 2001).

Whilst the magnocellular theory may appear a useful and attractive amalgamation of theoretical standpoints, it has been criticised. There is mixed evidence regarding the presence of auditory deficits in dyslexia, with many researchers failing to reliably identify such deficits in individuals with dyslexia (Heath, Hogben, & Clark, 1999; McArthur & Hogben, 2001) and Gibson, Hogben, and Fletcher (2006) have suggested that those with auditory deficits may be part of a subgroup. Ramus et al. (2003) estimated that the incidence of auditory deficits in dyslexia may be as low as 40%. Also, the magnocellular theory implicates ‘rapid’ auditory processing, measured by tasks tapping the perception of short or rapidly varying stimuli. The magnocellular system is thought to be vital to perception of such stimuli (Galaburda & Livingstone, 1993), and if magnocellular function is impaired in all individuals with dyslexia, deficits in the processing of such stimuli should be universal. Some studies, however, have shown this rapid processing to be intact in participants with dyslexia, whilst in others ‘slow’ auditory processing is found to be impaired (Adlard & Hazan, 1998; Schulte-Körne, Deimel, Bartling, & Remschmidt, 1998). This variance in the incidence and nature of auditory deficits suggests that these may not be prominent causal factors in dyslexia.

Another criticism levelled at the magnocellular theory concerns binocular coordination in children with dyslexia. Binocular coordination is a term used to describe how the two eyes move in relation to one another (Kirkby, Webster, Blythe, & Liversedge, 2008). Stein (2001) suggested that, through failure to develop a dominant eye, children with dyslexia exhibit poor binocular coordination, which is a significant contributing factor to reading difficulties. The implication of Stein's theory is that a perfect alignment of the two eyes with regards to fixation position is the optimal developmental state, however eye movement research has suggested that a small fixation disparity is common in adults (Liversedge, Findlay, White, & Rayner, 2008), with even greater disparities observed in younger readers (Blythe, Liversedge, Joseph, White, & Findlay, 2006). There is also little direct evidence to support the occurrence of poor binocular coordination in children with dyslexia. Kirkby, Blythe, Drieghe, and Liversedge (2011) used eye tracking to assess the extent to which poor binocular coordination contributes to reading difficulties associated with dyslexia. If the magnocellular theory is correct, increased fixation disparity (the distance between the fixation point of each eye) should be observed in children with dyslexia, on both a reading task and on a non-linguistic task that requires a similar pattern of eye movements to reading. Kirkby et al. (2011) used a dot-scanning task, which required a pattern of saccades and fixations similar to those observed in reading, in addition to a reading task. If children with dyslexia have poor binocular coordination, rather than any linguistic deficit, a similar pattern of binocular disparity should be observed in the linguistic reading task and the non-linguistic dot scanning task. It was found that children with dyslexia had an increased magnitude of fixation disparity when reading compared to dot-scanning, suggesting that any disruption to oculomotor control in reading reflects a difficulty with linguistically processing the text, rather than an oculomotor deficit. This finding suggests that poor binocular coordination is unlikely to hold a causal role in the reading difficulties associated with dyslexia.

It may be the case that different individuals with dyslexia have a different range of deficits that independently contribute to reading difficulties, and that each theory described above may only apply to a certain number of individuals with dyslexia. Ramus et al. (2003) used a multiple case study to examine the suggestions put forward by each of the theories described above, with the aim of identifying which type of deficit was most prevalent in dyslexia. Using a battery of psychometric, phonological, auditory, visual, and cerebellar tests, they demonstrated that all 16 participants with dyslexia performed poorly on phonological tasks such as a ‘spoonerism’ task, requiring participants to swap the initial letters of two words in a pair, and nonword repetition tasks relative to controls. They also found that phonological impairment could cause reading dysfunction in the absence of sensory or motor abnormalities, as was the case in five of the participants. This clearly suggests impairment in phonology is a core marker of dyslexia. It was also found that few participants showed specific motor disabilities. Administering tests such as a bead threading task and a repetitive finger-tapping task, Ramus et al. (2003) found that only four participants performed poorly across each one. The researchers suggested that this low prevalence does not lend support to the cerebellar deficit theory, and raised the question of whether such deficits can be said to be a cause of dyslexia. With regard to visual magnocellular problems, only two participants within the sample demonstrated significant impairment on tasks of motion detection and contrast sensitivity (measuring the ability to distinguish between finer and finer increments of light versus dark), among others, and these two participants also had significant auditory and phonological problems, suggesting visual problems alone may not be a cause of dyslexia. Some researchers suggest, however, that generalised tasks of magnocellular function may in fact be measuring different processes, finding high variance between tasks (Goodbourn, et al., 2012).

In summary, a number of theories regarding the causes of dyslexia have been critically discussed. In the previous sections of this thesis, a strong role for phonological processing in word identification and reading development has been demonstrated, and this is further supported by evidence in this section suggesting impaired phonological processing is a factor in dyslexia. The strongest current theory for the reading difficulties associated with dyslexia is the phonological deficit hypothesis. Deficits in phonological tasks are robustly found in individuals with dyslexia (Ramus et al., 2003; Snowling, 2000), whereas this is not the case with other sensory tasks. The main issue with each of the three theories described above is the inability of each to explain all symptoms of dyslexia. The phonological deficit hypothesis cannot account for motor or sensory problems in dyslexia (Stein, 2001) and the magnocellular theory accounts for these problems but cannot explain why they are not universal across dyslexics. The multiple case study approach used by Ramus (2003) allows the prevalence of each type of deficit to be estimated, and it has been demonstrated that phonological deficits are the most common in dyslexia. This type of evidence, whilst acknowledging the heterogeneity in dyslexia, indicates that the phonological deficits hypothesis is the strongest current account of the reading difficulties associated with dyslexia. Traditional theories have been discussed in turn, but I will now look at a relatively modern theory, and what it can reveal regarding the causes of dyslexia, and conclude this section with a brief consideration of difficulties in interpreting data in the field of dyslexia.

The temporal sampling framework

The discovery of an underlying cause that links the deficits reliably observed in dyslexia would clearly represent a major breakthrough. Strong evidence for a phonological processing deficit has been found, and more recent theoretical positions on dyslexia have investigated this deficit further. One of the more prominent theories to emerge in recent years is the temporal sampling framework (TSF; Goswami, 2011). The TSF's key assumption is that the core deficit in dyslexia is phonological in nature, but the focus on findings from auditory neuroscience has implicated differences in how speech is processed in individuals with dyslexia, and how this has a major impact on the development of phonological processing abilities from birth and across languages. The TSF has particular relevance for this thesis, and is discussed in detail as it focuses on phonological processing difficulties in particular.

The TSF itself builds upon the assumptions of the multi-time resolution model of speech processing (Poeppel, Idsardi, & van Wassenhove, 2008). According to this model, speech is processed via several distinct networks of neurons in the auditory cortex. The oscillations (the rhythmic electrical activity generated in response to a stimuli, with high and low excitatory activity) of each of these networks at different frequencies help to encode different units of the speech signal, such as syllables and phonemes. The speech signal is not entirely uniform, but neither is it stochastic, and events such as syllables occur at roughly the same rate regardless of speaking rate (Soltész, Szűcs, Leong, White, & Goswami, 2013) For instance, syllables begin roughly every 200ms during speech (Ghitza & Greenberg, 2009), and networks of neurons that oscillate at the corresponding rate (between 4-10Hz, Theta band) are, thus, responsible for perceiving syllables. Stressed syllables, by comparison, occur roughly every 500ms, and thus networks of neurons that oscillate at lower frequencies (1-4Hz, Delta band) are implicated. In order for the speech signal to be perceived as unitary, these distinct networks operate in parallel, and each demonstrates a pattern of phase locking. For instance, whilst perceiving speech, Theta band neurons will begin to oscillate at the rate at which syllables occur, and Delta band neurons at the rate at which stressed syllables occur. The timing of the high excitability phases of the oscillations thus becomes ‘locked’ to the oscillations in frequency of the speech signal, allowing efficient encoding of speech to take place. The overall process described is known as temporal coding.

The TSF focuses upon deficits in dyslexia with regard to the process of phase locking, and in particular phase locking in neural networks responsible for encoding syllables (Delta and Theta band networks), to better understand the basis of the phonological deficit described in this section. A very robust cross-linguistic finding is that individuals with dyslexia have particular difficulty in processing the rate of change of amplitude in the speech signal (also known as rise time). Rise times are important cues within the speech signal that aid the process of temporal coding, and beat detection tasks have demonstrated that children with dyslexia are significantly poorer than typically developing peers at entraining themselves to rhythmic stimuli (Goswami et al., 2002; Muneaux et al., 2004; Goswami et al., 2011). This rise time deficit is proposed to lead to impaired phase-locking in Theta band networks (important for processing syllables), and that reading difficulties arise due to this atypical pattern of auditory processing from birth. Goswami (2011) suggested that this pattern negatively impacts the development of phonological awareness, demonstrated in section 1.1 to be a crucial process in learning to read (Castles & Coltheart, 2004; Mann, 1984; Mann & Liberman, 1987; Wagner & Torgesen, 1987; Wagner, et al., 1994).

There is a great deal of evidence to suggest auditory processing deficits are common in dyslexia. Adults and children with dyslexia are significantly poorer at discriminating stressed syllables from unstressed syllables (Goswami, Huss, Mead, Fosker, & Verney, 2013; Leong, Hamalainen, Soltész, & Goswami, 2011), and both children and adults with dyslexia have demonstrated impairments in rhythmic entrainment tasks (such as finger tapping) at lower syllable-relevant frequencies (Goswami & Thomson, 2008). These findings suggest deficits in the processing of syllables in adults and children with dyslexia, but the clearest evidence comes from on-line measures of auditory processing as described below.

Hamalainen, Soltész, Szűcs, and Goswami (2012) played white noise at different temporal rates to adults with and without dyslexia, and measured neuronal oscillations in a simple listening paradigm. At a lower frequency (2Hz), the neuronal oscillations of participants with dyslexia showed weaker entrainment to the white noise, suggesting impaired phase-locking at low frequencies. Interestingly, participants with dyslexia demonstrated even stronger entrainment at higher frequencies (up to 10Hz) than controls, perhaps suggesting a compensatory mechanism at these higher frequencies (see also Power, Mead, Barnes, & Goswami, 2013). A similar result has been obtained using event-related oscillatory electroencephalography (EEG), where evidence has been found of impaired phase-locking at low frequencies (Soltész, Szűcs, Leong, White, & Goswami, 2013). These results suggest that individuals with dyslexia may be impaired in their perception of certain phonological units, which may lead to poorer representations of phonological information in the lexicon.

Moreover, a recent longitudinal study has used structural neuroimaging to examine differences in brain structure between children with and without dyslexia. Clark et al. (2014) followed a sample of Norwegian children at familial risk of developing dyslexia, with the study crucially beginning prior to direct instruction in reading, and compared them to a sample of children at low risk of developing dyslexia. Scans taken prior to reading instruction demonstrated that the differences between the high and low risk samples were within sensory areas (the primary visual and auditory cortices), rather than within the areas traditionally considered important for reading (see Goswami, 2014). Children at risk of dyslexia had lower cortical thickness in these areas than children at low risk. In addition to this, the only structure where group differences were reliably observed throughout the study was in the primary auditory cortex, with children who went on to develop dyslexia showing thinner Heschl's gyri. Clark et al. (2014) suggested that children at risk of developing dyslexia have a reduced capacity for the processing of auditory information prior to learning to read, and this study supports the assumption of the TSF (Goswami, 2011) that auditory processing difficulties from birth may cause dyslexia.

The TSF is a relatively new theory, but it is able to account for many of the effects typically observed in individuals with dyslexia. The implication of the proposed deficits in processing rise-time is demonstrated by a reduced ability in dyslexia to differentiate between stressed and unstressed syllables (Goswami et al., 2013; Leong et al., 2011), and this also explains deficits in rhythmic timing (Goswami & Thomson, 2008). It also crucially explains the prevalence of dyslexia across orthographies, suggesting atypical auditory processing from birth leads to early difficulties in processing speech that impacts upon the development of phonological awareness, a process crucial in learning to read (Castles & Coltheart, 2004; Mann, 1984; Mann & Liberman, 1987; Wagner & Torgesen, 1987; Wagner et al., 1994).

Difficulties in interpreting data

Given that dyslexia is characterised by varying levels of auditory, visual, motor, and phonological deficits, there is some debate regarding the importance of the tasks used to test each (Frith, 1999; Ramus & Szenkovits, 2008). While for the purposes of this review I have focused on dyslexia largely as a reading disorder, there is evidence for its neurological basis (Frith, 1999; Goswami, 2011). It is, therefore, difficult to compare and contrast theories that focus their attention on abnormalities at different levels. Frith (1999) suggests three levels of description- the biological, cognitive, and the behavioural. Within her framework, environmental factors can interact at one or more of these levels. Causal hypotheses can thus be labelled as biological, cognitive, or behavioural in nature, and it is possible to identify which theories are compatible with each other. For instance, the magnocellular theory assumes an abnormality at the neural level, whereas the phonological deficit theory suggests an abnormality at the cognitive level, and doesn't address the role of neurological deficits; both theories are compatible with each other, and Frith (1999) suggested that attempting to define dyslexia at a single level will always lead to paradoxes, as evidenced by the lack of overall concurrence in the literature.

Nicolson and Fawcett (2005) also suggested that the phonological deficit theory, magnocellular theory and their own cerebellar deficit theory attempt to explain dyslexia at different levels, and are thus not incompatible- the phonological deficit theory considers dyslexia at a cognitive level, whereas the magnocellular and cerebellar deficit theories consider neurological factors. As the magnocellular and cerebellar deficit theories focus on different brain areas of origin for dyslexia, they are certainly not mutually exclusive when considered together. It is well documented that the magnocellular system has significant input into the cerebellum (Stein & Glickstein, 1992; Stein & Walsh, 1997), and the deficits observed in dyslexia may be due to faulty input or faulty reception, or even an interaction between the two (Stoodley & Stein, 2011).

It has been suggested that demonstrating group differences on sensory and motor tasks is not sufficient in attempting to explain dyslexia, as such differences may not necessarily represent a causal deficit (Ramus, White, & Frith, 2006). Ramus and Ahissar (2012) suggested that the reason for the abundance of theories of dyslexia is the observation of a dyslexic deficit on a huge variety of tasks. It may be an overgeneralisation to consider findings of poor performance in isolation, and Ramus and Ahissar (2012) stressed the need to explain and predict cases where participants with dyslexia perform normally in addition to those where they show deficits. Reviewing dozens of tasks relating to phonological, auditory, and visual deficits, Ramus and Ahissar (2012) concluded that in order for a task to be an effective measure of a deficit, it must be simple, subtle, and sensitive, but that it is tenuous to attribute variance in performance to a single type of processing. They argued that even the simplest of tasks, such as frequency discrimination between two tones, may involve multiple processes such as audition, attention, and short term memory.

To summarise, this section has considered dyslexia in terms of its diagnostic profile, potential subtypes, and proposed causes. The phonological deficits hypothesis is weakened by its inability to sufficiently explain sensory and motor dysfunctions that are observed in some individuals with dyslexia, but remains by far the strongest theoretical position for explaining the reading difficulties associated with dyslexia. The wide range of auditory, visual, and motor deficits observed in dyslexia are captured in part by the magnocellular theory, but it cannot account for the absence of such deficits in some individuals with dyslexia, and its claims regarding binocular coordination have received criticism. The cerebellar theory suffers from both of these limitations; able to explain neither sensory and motor deficits nor the heterogeneity between individuals with dyslexia. The conclusion that the phonological deficit theory is the strongest of the explanations for the causes of the reading difficulties associated with dyslexia corresponds to evidence discussed in Section 1 regarding the role of phonology in written word identification. New theories are emerging regularly however, such as the TSF, which will generate more research into the exact nature of phonological processing deficits associated with developmental dyslexia.

1.3: The Role of Phonology in Reading

As discussed in Sections 1.1 and 1.2, successful reading development is linked to phonological awareness. The potential role held by a word's phonological characteristics in its identification is, however, an important subsequent issue. This section will address theoretical standpoints on the role of a word's phonology in its identification.

The concept of a mental lexicon, a store comprised of lexical entries for all words known to a reader, is widespread in the field of psycholinguistics, and various models have conceptualised the process of accessing an entry in the lexicon to identify a written word (lexical access; e.g., Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Forster, 1976; McClelland & Rumelhart, 1981; Morton, 1969, 1970). A historical outline of the differing assumptions of each of these models is beyond the scope of this review, however, one common consensus is that semantic, orthographic, and phonological information is all retained within the lexicon. In principle, this allows for the possibility that a reader's knowledge of the phonological characteristics of a lexical entry may facilitate lexical access (pre-lexical role for phonology; phonological recoding). Alternatively, phonological information may only become available to a reader following lexical access, and orthographic information may be the only determinant of word identification (post-lexical role for phonology; direct access). The following subsection will focus upon these alternate possibilities.

The time course of phonological processing

The difference between these two alternative hypotheses concerns the time course of phonological processing, and, specifically, whether the phonological characteristics of a word are available to a reader prior to or following lexical access. If phonological characteristics are available to a reader prior to lexical access, then it may be the case that a word's phonology plays a role in its identification, although, as I will discuss, this is difficult to experimentally determine. Alternatively, the activation of a word's phonology may only occur following lexical access, in which case phonological information is directly retrieved with no role for recoding (in a process known as addressed phonology). It may be the case that phonological recoding occurs in some, but not all cases, of visual word recognition, and there may be a role for both processes (Coltheart et al., 2001; Seidenberg, Waters, Barnes, & Tanenhaus, 1984). Prelexically, phonological information is proposed to become available to a reader through the application of stored grapheme-phoneme correspondence rules (see Berent, 2013), in a process known as assembled phonology. A reader applies their knowledge of these correspondences to recode the orthographic form of a word into its phonological form, which may then aid lexical access. This section will address each of these theoretical standpoints.

A pure, direct account of lexical access would suggest that the lexical entry for a printed word is activated solely through recognition of its orthographic representation, with no prelexical influence of phonology. Some researchers have advocated such a framework (e.g. Bower, 1970; Kolers, 1970), but the experimental evidence that has accumulated in the intervening years does not substantiate the notion that phonological recoding is entirely absent prelexically. It has also been suggested that the arguments in favour of a direct access mechanism were built upon a lack of evidence for phonological recoding, rather than strong evidence for a direct access mechanism (Humphreys & Evett, 1985; Luo, Johnson, & Gallo, 1998). A less rigid version of this framework has also been hypothesised whereby direct access from orthography is the typical method of achieving lexical access, but that under certain circumstances phonological information may be used. Evidence for such an account was put forward by Baron (1973) from an experiment in which participants were required to classify whether presented phrases made sense or were nonsensical. Baron (1973) firstly found that subjects were no faster in classifying phrases with nonhomophonic errors (e.g., *our no car*) as nonsense than the phrases with homophonic errors (e.g., *our knew car*). If phonological recoding was a necessary prelexical process, Baron (1973) argued that phonologically incorrect phrases should be identified as nonsensical faster than phonologically correct phrases, due to interference from the correct phonology. Secondly, however, error rates were higher on homophonic phrases when compared to correct phrases (e.g., *our new car*). Baron (1973) argued that phonological mediation was not a necessary process for lexical access, although this process may occur under some conditions or in certain tasks (see also Green & Shallice, 1976; Martin, 1982).

A number of different tasks have been employed to study phonological recoding. For instance, naming tasks require a subject to pronounce a written letter string, often at speed, whilst lexical decision and semantic categorisation tasks demand that a decision be made on a letter string's status as a lexical entry, or as an exemplar of a particular category. These extraneous demands, which do not occur during normal reading and word identification, have led to concerns over the ease with which results from different paradigms can be reconciled (Leinenger, 2014). Evidence from and criticism against these various tasks will be discussed below.

Naming tasks. Naming tasks typically require a participant to pronounce a printed stimulus with latency and accuracy the dependent measures. This task has been employed in conjunction with a priming procedure, and using homophones as stimuli, to assess the role of phonology in a word's identification. The rationale behind this approach is that naming can only occur following lexical access, and that naming latency can, thus, be used as an index of this process. For instance, Lesch and Pollatsek (1993) had participants name target words (e.g., armor) after the presentation of a prime, either an associate word (e.g., knight), a homophone of that associate (e.g., night), an orthographic control word (e.g,. flight) or an unrelated word (e.g,. branch). They also varied the presentation duration of the prime word (either 50ms or 200ms), finding that at short prime durations the target was named faster following both the associate and the homophone primes compared to the orthographic control. At longer prime durations, associate priming was still evident, but there was no longer an effect of homophone priming. Lesch and Pollatsek (1993) concluded that phonological recoding contributed to lexical access, but at longer prime durations on-going orthographic coding had identified the homophone prime as semantically unrelated to the target, inhibiting the phonological form of the prime. This conclusion was supported by the finding that pseudohomophone priming, using nonwords with no lexical entries to bypass this inhibition, occurred at longer prime durations (250ms; Lukatela & Turvey, 1994). Moreover, phonological priming has been observed in a naming task when phonological overlap between prime and target is only partial (e.g. first syllable in a two syllable word; Carreiras, Ferrand, Grainger, & Perea, 2005).

The effect of regularity (how closely the pronunciation of a word follows grapheme-phoneme correspondence rules) has also been investigated extensively using naming tasks. The rationale behind studying regularity is that if phonological recoding always precedes lexical access, a robust advantage should be demonstrated for regular words that can be identified using assembled phonology over irregular words to which grapheme-phoneme rules do not apply, even in tasks that do not explicitly require phonological recoding. If words are identified from their orthographic form only, no difference should be observed between regular and irregular stimuli in word identification tasks (Stanovich & Bauer, 1978). Increased naming latencies for irregular or exception words over regular words has been observed in both adults (Andrews, 1982; Gluschko, 1979; Gough & Cosky, 1977; Parkin, 1984; Seidenberg et al., 1984; Stanovich & Bauer, 1978) and in developing readers (Schmalz, Marinus, & Castles, 2014; Waters, Seidenberg, & Bruck, 1984). The use of a naming task has, however, been criticised, with Seidenberg et al. (1984) suggesting that the explicit requirement of pronunciation means that phonological processes occur that may not be present during silent reading, and that naming latencies may simply reflect the amount of time taken to execute a motor response, rather than reflecting lexical access (Leinenger, 2014). Moreover, subjects may be able to perform the task by simply relying on their knowledge of grapheme-phoneme correspondences, rather than necessarily relying on lexical access (Jared & Seidenberg, 1991). Tasks that more explicitly rely on lexical access, such as lexical decision tasks, are discussed next.

Lexical decision tasks. A lexical decision task (LDT) is particularly frequently used, requiring participants to decide as quickly as possible, usually nonverbally, whether a printed letter string is a word or not. It has been argued that this task necessitates lexical access (Coltheart, Besner, Jonasson, & Davelaar, 1979, though see Balota & Chumbley, 1984), as a 'word' decision can only be reached after accessing the lexicon. A common finding from this methodology concerns homophones (words that share pronunciation with other words but differ in their orthographic forms and semantics, e.g., made-maid) and pseudohomophones (nonwords that share pronunciation with a real word, e.g., brain-brane). For instance, Rubenstein, Lewis, and Rubenstein (1971) found that participants showed longer latencies and increased error rates for nonwords that were homophonic with a real word (e.g., *brume*) compared to nonwords that were not (e.g., *relp*). Rubenstein et al. (1971) also found that response latencies were longer for homophones compared to nonhomophones (see also, Meyer, Shvaneveldt, & Ruddy, 1974). In each case, the authors argued that shared phonology of the presented nonword with a genuine lexical entry delayed response times, concluding that "orthographic representations in the internal lexicon are secondary to the phonological representations" (Rubenstein et al., 1971, p. 655). This pseudohomophone effect has proven to be robust in LDTs (Coltheart, Besner, Jonasson, & Besner, 1977; McCann, Besner, & Davelaar, 1988; Stone & Van Orden, 1993), with the explanation that longer latencies are observed for pseudohomophones due to the resolution of the discrepancy between phonological information and orthographic information corresponding to a lexical entry (Ziegler, Jacobs, & Kluppel, 2001).

LDTs have also been used to study other variables of words, such as their regularity. Results from LDTs have been mixed, with some finding the described regularity effect, which is an advantage for regular words over irregular words in response latency (Bauer & Stanovich, 1980; Seidenberg et al., 1984; Stanovich &

Bauer, 1978), whereas others have not (Coltheart, Besner, Jonasson, & Davelaar, 1979). It may be the case that other variables are confounded with regularity, such as word frequency. Seidenberg et al. (1984) found longer response latencies for irregular words compared to regular words, but only for low frequency items. As low frequency words take longer to identify (Forster & Chambers, 1973), Seidenberg et al. (1984) suggested that phonological recoding was a slower strategy than direct orthographic access, and that retrieval of high frequency lexical entries can occur prior to any interference from phonological recoding (see also Waters, Seidenberg, & Brook, 1984). These results suggested that the time course for orthographic and phonological processing may be different, and that direct access via a word's orthographic form is possible for words that are encountered often during reading.

Semantic categorisation and error detection tasks. Another methodology that has been used to investigate phonological recoding is semantic categorisation. This task requires participants to decide, under time constraint, whether a presented letter string is an exemplar of a predefined category or not. This task does not necessitate the activation of phonological information in the way that naming tasks do, and also comes with the advantage that in order for subjects to make a decision, access to semantic information (i.e., lexical access) must be achieved. Some of the strongest evidence for the argument that phonological information helps to facilitate lexical access comes from this paradigm, and in particular from the studies of Van Orden and colleagues. Van Orden (1987) used homophonic examples for a particular category (e.g., presenting 'hare' for the category 'part of a human body', along with correct examples such as 'hair'), finding an increase in the number of false positive errors on homophone items compared to orthographic controls even when targets were presented for short durations and backward masked. Van Orden, Johnston, and Hale (1988) also generalised this finding to the pseudohomophones of correct category examples (e.g., '*sute*' for 'item of clothing'). Van Orden and colleagues argued that the application of grapheme-phoneme rules activated the lexical entry of the correct category exemplar, in spite of the conflicting orthographic information. Importantly, the finding of a similar pattern for pseudohomophones directly implicates this as a prelexical process, as pseudohomophones have no lexical entry.

Jared and Seidenberg (1991) have, however, disputed the conclusion that phonological recoding is mandatory for all words. By broadening the categories used in the semantic categorisation task to 'object' or 'living thing' only, Jared and Seidenberg (1991) found a greatly reduced, but still significant, rate of false positive errors on homophone items. For instance, when the category was '*car part*', significantly more false positive errors were made (8.3%) compared to when the category was '*living thing*', and Jared and Seidenberg (1991) suggested that the use of very specific categories led to the generation of sets of possible semantic candidates by participants, which may account for the number of false positive errors. Moreover, and in line with research from other methodologies discussed, Jared and Seidenberg (1991) found that high frequency homophone foils produced no more false positive errors than spelling control words, whereas the effect was found for low frequency words. Jared and Seidenberg (1991) suggested that phonological recoding is not mandatory during word identification, and that only low frequency items may be subject to this process.

Finally, a more recent study by Jared, Ashby, Agauas and Levy (2015) used an error detection task. Children, aged between ten and eleven, were asked to read sentences in a proofreading task, some of which contained errors. Half of all errors were pseudohomophones, and the other half were spelling control words. Jared et al. (2015) found that children were less likely to identify pseudohomophone errors than spelling control errors, regardless of reading ability. This study demonstrates that even when participants implicitly expect there to be errors in a text, they are less likely to notice them if these errors preserve the phonology of a correct word in that context.

To summarise, each methodology has provided a varying pattern of results. In naming tasks, it has been clearly demonstrated that the phonological characteristics of stimuli affected naming latencies, both in terms of a pseudohomophone advantage (Lukatela & Turvey, 1994), and through a robust demonstration of the regularity effect in adults and developing readers. A pseudohomophone effect has been consistently demonstrated in LDTs (Coltheart et al., 1977; McCann et al., 1988; Rubenstein et al., 1971; Stone & Van Orden, 1993), but results concerning regularity have been less clear. As discussed, the issues at stake are whether the phonological characteristics of a word are available to a reader prior to or following lexical access, and whether these characteristics are used to retrieve the lexical entry. The finding that response latencies and error rates are increased for pseudohomophones over control words suggests that phonological recoding occurs prior to lexical access, even in a task that does not explicitly require subjects to activate a word’s phonological characteristics. A consistent regularity effect in LDTs would suggest that the process of assembled phonology occurs prior to lexical access, and that the failure of this strategy to identify irregular words leads to a difference in response latencies or accuracy modulated by a word’s regularity. Such a pattern is not consistently found for all words, however, leading to the suggestion that words encountered often in print may be identified directly from their orthographic form. Paradigms that seek to adhere more closely to the process of normal reading, removing all decision and output components, are discussed next.

Eye tracking during silent reading. Eye tracking as a paradigm for studying reading will be discussed at length later in this thesis, but, in short, it has been very robustly demonstrated that eye movement behaviour is influenced by cognitive processing (Liversedge & Findlay, 2000; Rayner, 1998). By measuring fixation durations on words in sentences, inferences can be made about cognitive processing during lexical identification, and by manipulating the phonological characteristics of words in sentences, the potential role of phonological recoding can be studied using a task that remains relatively naturalistic. For instance, Rayner, Pollatsek, and Binder (1998) presented participants with passages in which a target word was one member of a homophone pair of varying orthographic similarity (e.g., brake-break). In this way, only one member of the homophone pair made sense within the context of the sentence (e.g., slammed on the break/brake). Initial fixation durations on these words did not significantly differ when the preceding sentence context was highly constraining to the other member of the homophone pair, although measures of total processing time were increased for the contextually incorrect homophone. This is strong evidence to suggest a prelexical role for a word's phonology, as no indication of erroneous orthography was detected in early processing measures. Moreover, it was found that orthographic control words (e.g. bread) were fixated for significantly more time than homophones, suggesting that the observed effect is not simply due to orthographic overlap between the two members of the homophone pair, but due to their shared phonology (see also Blythe, Pagán, & Dodd, 2015, Jared et al., 2015).

Regularity has also been studied using eye tracking, with both Inhoff and Topolski (1994) and Sereno and Rayner (2000) finding that irregular words were fixated for longer than regular words in sentences. Both studies observed this effect in first fixation duration (the duration of the very first fixation on a word regardless of additional fixations), a measure used to assess first pass reading behaviour (as opposed to instances in which the subject has returned to re-read the word from later in the sentence). Moreover, Sereno and Rayner (2000) found evidence for a regularity by frequency interaction such that the difference in fixation times between regular and irregular target words was greater for low frequency words, a result in concurrence with LDT findings (Seidenberg et al., 1984). Sereno and Rayner (2000) also provided evidence that a word's phonological characteristics are processed to some extent prior to its direct fixation during sentence reading, using the boundary paradigm. In the boundary paradigm (Rayner, 1975) a reader is presented with a sentence containing an invisible boundary before a word. That word may be a prime for an eventual target, a control word, or a series of characters. When a saccade crosses the boundary the original word or letter string is replaced with the target word. This process denies the reader the ability to parafoveally pre-process the upcoming word. Researchers can then vary the degree of overlap between the target prime and the target itself, to investigate how readers parafoveally process a variety of factors such as orthographic and phonological characteristics. Sereno and Rayner (2000) observed a regularity by frequency interaction, but only when participants received a valid preview (instances in which the prime and target words were identical). In such instances, reading times on low frequency regular words were shorter than low frequency exception words, and this effect was not observed for high frequency stimuli. Sereno and Rayner (2000) suggested that this provides strong evidence for the parafoveal processing of phonological information, and suggested that phonological recoding is an important aspect of lexical identification.

Additional studies using the boundary paradigm have also found that phonological recoding begins prior to direct fixation in skilled adult readers. For instance, Pollatsek, Lesch, Morris, and Rayner (1992) used homophones (e.g., *beech*) or orthographic control words (e.g., *bench*) as previews for the eventual fixated target '*beach'*. Pollatsek et al. (1992) found that participants fixated the target word for a significantly shorter period of time when it was previewed by a homophone compared to a control word, suggesting that phonological recoding occurred prior to fixation on the target. This finding has been replicated both in English and in other languages (Chace, Rayner, & Well, 2005; Miellet and Sparrow, 2004; Tsai, Lee, Tzeng, Hung, & Yen, 2004). This study provides strong evidence that phonological recoding begins prior to lexical access.

Evidence from eye tracking has clearly demonstrated that the phonological characteristics of a word are available to a reader prior to lexical access, and that the use of this information may mediate lexical identification. Readers demonstrated equivalent first pass fixation durations on members of a homophone pair under certain conditions (Rayner et al., 1998) and displayed evidence for phonological processing on upcoming words in the sentence prior to direct fixation (Miellet & Sparrow, 2004; Pollatsek et al., 1992; Sereno & Rayner, 2000). This second finding in particular implicates a prelexical role for a word's phonology, and suggests that phonological recoding may play a role in activating lexical entries during reading.

To conclude, a variety of tasks have been employed to understand phonological recoding, and whether or not it is a prelexical process that facilitates lexical access. The extent to which these tasks require the participant to lexically access words is also an issue that has been discussed, along with the various extraneous demands of each. It is abundantly clear from LDTs, naming, and semantic categorisation that subjects activate phonological information to complete each task (Rubenstein et al., 1971; Seidenberg et al., 1984; Van Orden, 1987; Van Orden et al., 1988), but, on the basis of these tasks alone, it is difficult to inarguably conclude that phonological recoding is a prelexical process. Whilst some common findings are observed between these tasks, the extent to which extraneous demands (e.g., pronunciation, decision components) may influence phonological recoding is unclear. The clearest evidence, therefore, is provided by tasks that remove extraneous demands and attempt to study word identification in the most naturalistic way possible. Eye tracking paradigms have unequivocally demonstrated a prelexical role for a word's phonology, and that phonological recoding can occur even prior to a word's direct fixation (Chace et al., 2005; Miellet & Sparrow, 2004; Pollatsek et al., 1992; Rayner et al. 1998). These studies observed these effects in the absence of additional task-related demands on participants, and represent a closer approximation to the process of normal reading than the other tasks discussed.

Taken together, all of the evidence reviewed has strongly implicated phonological recoding as a prelexical process, with some evidence to suggest that this process may facilitate lexical access itself (Pollatsek et al., 1992; Van Orden, 1987; Van Orden et al., 1988). Another common finding, however, is that phonological recoding and orthographic processing may occur in parallel, and, in the case of words encountered often, lexical access may occur via processing a word's orthography prior to phonological recoding (Jared & Seidenberg, 1991; Seidenberg et al., 1984; Sereno & Rayner, 2000).

1.4: Summary

The aim in this chapter has been to review the literature in which a robust link between phonological processing and reading has been established. The first section focused upon the nature of phonological processing skills, how these skills are manifested before a child learns to read, and their influence on a child's reading development. A number of studies have demonstrated that preschool children have some awareness of phonological units (Fox & Routh, 1975; Lenel & Cantor, 1979; Liberman et al., 1974; Lonigan et al., 1998; MacLean et al., 1987) as a child's introduction to spoken language is made long before explicit reading instruction is undertaken.

The question of to what extent this pre-existing knowledge contributes to the ease with which children acquire reading has also been addressed. The evidence presented from longitudinal research has demonstrated beyond doubt a link between phonological processing and reading ability, but more specifically it has been shown that a child's phonological processing abilities, and in particular their awareness of and ability to manipulate phonemes, is causally linked to later reading ability (Castles & Coltheart, 2004; Mann, 1984; Mann & Liberman, 1987; Wagner & Torgesen, 1987; Wagner, et al., 1994). It has also been found that specific training procedures to boost phonological awareness are linked with an improvement in reading skill (Bus & Van Ijzendoorn, 1999; Ehri, Nunes, Stahl et al., 2001; Ehri, Nunes, Willows et al., 2001).

The correlational nature of much of this research inherently leads to the fact that the relationship between phonological processing and later reading ability can be interpreted in multiple ways. It is possible that learning to read in itself boosts phonological processing abilities (Greenberg et al., 1997; Greenberg et al., 2002; Morais et al., 1979), and taking account of all the evidence, it appears that the relationship may be bidirectional (Wagner et al., 1994). An early awareness of phonological units seems to lead to improved reading outcomes, but it is also clear that explicit instruction gives children a far better awareness of phonemes, which in turn aids reading. Theories of reading development have also been considered. Stage theories (Frith, 1985) and phase theories (Ehri, 1989, 1991, 2005) have been evaluated, with these structured accounts of learning to read generally favouring one strategy or skill in a particular stage or phase. The causal connections theory (Goswami & Bryant, 1990) and the psycholinguistic grain size theory (Ziegler & Goswami, 2005) have also been discussed, with each emphasising the importance of phonological awareness in learning to read.

The topic of developmental dyslexia has also been raised, and whilst issues surrounding the diagnosis and root causes of dyslexia remain a subject of theoretical debate, there is a great deal of experimental evidence linking underlying phonological deficits with the reading difficulties associated with dyslexia. While the aim in the first section of this chapter was to demonstrate the importance of phonological processing in learning to read, the aim in the second section was to strengthen this link further by providing an example of a reading disability that, evidence strongly suggests, is caused by phonological processing deficits. More recent developments have implicated abnormalities in the processing of speech as a potential cause of the reading difficulties associated with dyslexia (Goswami, 2011). Taken together, the strongest explanation for these reading difficulties is provided by the phonological deficits hypothesis.

That there is a prelexical role for a word's phonology in its identification is now widely accepted (Meyer et al., 1974; Rubenstein et al., 1971, Van Orden, 1987; Van Orden et al., 1988, see Frost, 1998, for a review). Evidence from lexical decision, semantic categorisation, and naming tasks has demonstrated that phonological information is activated during these tasks, although arguments that these tasks are not explicitly demonstrative of lexical access have also been discussed. The clearest evidence is provided by eye-tracking studies, which have very clearly shown that a word's phonology is activated prelexically (Rayner et al., 1998), and often prior to direct fixation (Miellet & Sparrow, 2000; Pollatsek et al., 1992; Sereno & Rayner, 2000). On the basis of evidence from all paradigms discussed, phonological recoding has robustly been shown to be a prelexical process. The issue of whether phonological recoding is a mandatory process that facilitates lexical access has also been discussed, with evidence suggesting that the characteristics of the word being read may determine whether phonological recoding occurs (Seidenberg et al., 1984).

This chapter has demonstrated the importance of phonological awareness in learning to read and in the word identification process of skilled readers. The following chapters of this thesis describe two experiments designed to test phonological processing skills in both typically developing children and children with dyslexia, both using eye-tracking. The next chapter of this thesis will give an introduction to eye movement research and the link between eye movements and cognitive processing.

Chapter Two: Eye movements in reading in skilled adult readers, typically developing children, and children with dyslexia

The use of eye tracking as a research method has grown significantly in the past 40 years, and this technique is now widely accepted as an objective means of providing insight into on-going cognitive processing during reading (Rayner, 1998, 2009). As mentioned in previous sections, some tasks used to investigate word identification have required participants to perform actions that may not typically occur during normal reading. For instance, in a naming task pronunciation latency would be measured (e.g., Seidenberg, Waters, Barnes, & Tanenhaus, 1984), thus the articulatory motor response to a stimulus is used as the index for its lexical identification. By recording eye movements as participants silently read sentences, all pronunciation or decision components are removed from the task, allowing a more naturalistic method for studying the cognitive processes underlying reading. In this section, I will describe the basic characteristics of eye movements during reading, considering in turn eye movement behaviour in adults, both typically developing children and children with dyslexia.

2.1. Eye Movement Behaviour in Skilled Adult Readers

The two most basic components of eye movements during reading are the movements of the eyes themselves (saccades) and the brief pauses between saccades where the eyes stay fairly motionless and information is visually encoded (fixations). A saccade's function is to either bring a new region of text to the point of fixation, or to return to a previous word in the sentence, and during these rapid, pre-planned movements, very little visual information is sampled due to a retinal blur associated with the high velocity of the eye movement, leading to a suppression of input (Matin, 1974, though see Campbell & Wurtz, 1978; Uttal & Smith, 1968). For adults, fixations in reading typically last between 225 and 250ms (Rayner, 1998), saccades take around 175-200ms to plan and initiate (Becker & Jürgens, 1979), and saccade duration (the time taken to move the eyes) varies as a function of distance moved, but typically in reading takes around 30ms (Rayner, 1978). This pattern of saccadic eye movements is necessitated by anatomical constraints within the retina, where the point of highest-acuity vision (the fovea) occupies only around 2^{o} of central vision. Visual acuity continuously decreases as a function of retinal distance from the fovea, with the parafovea extending a further 5^{o} outwards in both directions from the fovea, followed by the periphery, where little visual information can be sampled (Rayner, 1998, 2009). As I will discuss, both foveal and parafoveal pre-processing are important in skilled reading.

Whilst reading in English, the majority of saccades are made from left-to-right, following the sequential order of words in sentences. It has been found that saccade amplitude (distance of a saccade) is not modulated by viewing distance (Morrison & Rayner, 1981), and the typical saccade amplitude is seven to nine characters, but is contingent on the processing demands imposed by the text itself (Rayner, 1998, 2009). While the majority of saccades are made from left-to-right, a small proportion (10-15%) of leftward saccades (regressions) are made, either within the currently fixated word or to the previous words in the sentence (Rayner, 1998, 2009; Vitu & McConkie, 2000). Longer regressions to previous words within the sentence typically occur due to difficulties in understanding the currently fixated word or the text itself (see Mitchell, Shen, Green, & Hodgson, 2008), and the reader must return to a previous region to disambiguate it, as demonstrated by increased regression rates in the disambiguation regions of sentences (Frazier & Rayner, 1982; Traxler, Pickering, & Clifton, 1998). As the text being read becomes more syntactically difficult or ambiguous, fixation durations and regression rates also increase (Rayner, 1998). As I will discuss in this section, the finding that the lexical and syntactic properties of the text being read exert an influence on fixation times is strong evidence for a link between cognitive processing and eye movement behaviour.

That there is a tight link between moment-by-moment cognitive processes during reading and the eye movements of readers is now widely accepted (Rayner, 1998, 2009). For instance, a benchmark finding in eye movement studies is that a word encountered often in print (a high frequency word) is fixated for a shorter duration than a word encountered less frequently (a low frequency word; Brysbaert & Vitu, 1998; Just & Carpenter, 1980; Kliegl, Grabner, Rolfs, & Engbert, 2004; Rayner, 1998; Rayner & Duffy, 1986). Inhoff and Rayner (1986) suggested that the more frequently a word is encountered in print influences the speed with which that word's lexical entry can be accessed and the word thus identified, and that the frequency effect in eye movements during reading reflects the latency with which that word is lexically identified. Other word properties, such as a word's length or its predictability given the prior sentence context, have also been found to exert an influence on fixation durations, with shorter and predictable words fixated for shorter durations (Brysbaert & Vitu, 1998; Drieghe, Rayner, & Pollatsek, 2005; Ehrlich & Rayner, 1981; Rayner & Well, 1996). These findings demonstrate that the ease with which lexical identification is achieved is the primary determinant of fixation durations on words in sentences.

Additional evidence for the relationship between cognitive processes during reading and a reader's pattern of eye movements has been provided by use of the disappearing text paradigm. In such studies, an invisible boundary is placed between each of the words in a sentence. When a saccade crosses the boundary and the reader fixates a word, a set time is allowed to elapse before that word disappears completely, restricting the reader's foveal processing to the brief duration that the word is visible. These studies have demonstrated that participants require only a 50-60ms fixation on a word for reading to continue unperturbed in terms of speed or comprehension accuracy, despite the literal disappearance of the text (Liversedge et al., 2004; Rayner, Liversedge, & White, 2006; Rayner, Liversedge, White, & Vergilino-Perez, 2003). Participants' fixations on the subsequent blank spaces were also found to be modulated by word frequency, clearly demonstrating that the cognitive processes serving to lexically identify each word were the key determinant of when the eyes were moved.

There is also abundant evidence that, in addition to cognitive processing that occurs as readers fixate a word, readers engage in parafoveal pre-processing; that is, information from the parafovea is pre-processed whilst a reader fixates a word. Parafoveal pre-processing is a vital component of skilled reading, as it facilitates the lexical identification of a word during its subsequent direct fixation (see Schotter, Angele, & Rayner, 2012, for a review). Two paradigms in particular have been particularly useful in investigating the extent to which readers parafoveally pre-process upcoming information during reading, and the type of information that is pre-processed. Firstly, the moving window paradigm (McConkie & Rayner, 1975, see Rayner, 2014 for a review) is a gaze-contingent technique that allows the experimenter to vary the amount of parafoveal information available to a reader during any given fixation. A certain number of characters to the left and right of the point of fixation remain undisturbed, but all characters outside of this window are masked or visually degraded (e.g., replaced with x's), and the window moves in accordance with each fixation. By varying the window size, researchers are thus able to investigate the extent of the perceptual span (the region around the point of fixation from which useful information is extracted during reading) by observing at which window sizes reading is unperturbed, and the point at which reading is disrupted in terms of speed. Studies using this technique have clearly demonstrated that reading rate (words per minute) reaches asymptote at window sizes of around 14-15 characters to the right of fixation, and 3-4 characters to the left (Rayner, 1986; Rayner & Bertera, 1979). As mentioned previously, visual acuity declines as a function of distance from the fovea, and there is no anatomical account for this observed asymmetry in the perceptual span. Moreover, the opposite pattern of asymmetry has been observed in readers of right-to-left orthographies, such as Hebrew (Pollatsek, Bolozky, Rayner, & Well, 1981). Hebrew readers parafoveally pre-process information to the left of fixation to a greater extent than readers in left-to-right orthographies, reflecting the sequential order of words in sentences in each language. These findings strongly suggest that the allocation of attention during reading is the main determinant of the perceptual span's extent.

Secondly, the boundary paradigm (Rayner, 1975) is a gaze-contingent technique used to study the type of information processed in the parafovea. In this paradigm, the insertion of an invisible boundary in a sentence prior to a target word allows for a parafoveal preview of the target to be received by the reader that changes as a saccade crosses the boundary. Parafoveal pre-processing can thus be studied by varying the degree and nature of the overlap between the preview and the directly fixated target stimulus. The finding of a preview benefit, that is an advantage in terms of fixation durations on a word that was parafoveally available compared to when the parafoveal word was masked, is strongly indicative of the role of parafoveal pre-processing as a vital aspect of reading that facilitates lexical identification. This technique has been used to study the type of information that can be parafoveally processed. Whilst it does not appear that semantic information is typically processed parafoveally in alphabetic languages (Rayner, Balota, & Pollatsek, 1986; Rayner, Schotter, & Drieghe, 2014), there is evidence from the boundary paradigm to suggest that a word's orthographic (Hyönä, Bertram, & Pollatsek, 2004; McConkie & Zola, 1979) and phonological (Chace, Rayner, & Well, 2005; Fitzsimmons & Drieghe, 2011; Miellet & Sparrow, 2004; Pollatsek, Lesch, Morris, & Rayner, 1992) characteristics are typically processed to some extent prior to direct fixation. Findings from the boundary paradigm not only affirm that parafoveal pre-processing is facilitative to lexical identification during direct fixation, but that the orthographic and phonological characteristics of words are pre-processed prior to that word receiving a fixation.

Parafoveal pre-processing also allows words to be skipped during reading. A word is said to be skipped if it is not fixated during first-pass reading. Roughly a third of words are skipped by skilled adult readers, with content words (roughly 15% of the time) skipped less frequently than function words (roughly 65%, e.g., *the*, *and*, *for*; Brysbaert & Vitu, 1998; Rayner, 1998). Likelihood of a word being skipped is modulated by its predictability (Erlich & Rayner, 1981; Rayner, Slattery, Drieghe, & Liversedge, 2011) and length (Brysbaert, Vitu, & Drieghe, 2005), such that short and predictable words are skipped more often than long or unpredictable words. It appears that skipping represents instances in which the lexical identification of the skipped word was achieved solely through parafoveal pre-processing, and further confirms the importance of this pre-processing for fluent reading.

In summary, the pattern of eye movements that characterise skilled reading has been defined. A series of saccadic eye movements allows the reader to bring a new region of text to the fovea with each progressive fixation, and to return to previous regions of the text with each regressive fixation. It is abundantly clear that the pattern of eye movements a reader exhibits provides an index of the cognitive processes that occur during reading. A word's lexical characteristics, such as frequency (Brysbaert &

Vitu, 1998; Inhoff & Rayner, 1986; Just & Carpenter, 1980; Kliegl et al., 2004; Rayner, 1998; Rayner & Duffy, 1986), and predictability (Erlich & Rayner, 1981; Rayner et al., 2011; Rayner & Well, 1996) influence a) whether a word is fixated during reading, and b) how long that word is fixated for, and research utilising the disappearing text paradigm has demonstrated that fixation durations do not merely reflect visual uptake of information, but are an index of the cognitive processes of lexical identification that underlie reading (Liversedge et al., 2004; Rayner et al., 2006; Rayner et al., 2003). The importance of parafoveal pre-processing in reading has also been discussed, with studies demonstrating not only that this phenomenon is vital for fluent reading, but that orthographic and phonological information are processed prior to a word's direct fixation (Chace et al., 2005; Hyönä et al., 2004; Miellet & Sparrow, 2004; Pollatsek et al., 1992). The next section will discuss the similarities and differences observed between developing readers and skilled adults during reading.

2.2: Eye Movement Behaviour in Developing Readers

Compared to the vast number of studies that have documented eye movement behaviour during reading in skilled adults, there have been relatively few studies focusing on this pattern amongst younger readers. The paucity of studies into developing readers may be due in part to practical difficulties in collecting accurate eye tracking data from children, a process that involves sitting very still for a relatively long period of time and following explicit instructions, and also difficulty in recruiting sufficient samples of younger readers. With the development of video-based eye tracking technology, however, this is an absence that has begun to be addressed in recent years (see Blythe & Joseph, 2011, for a review), with a pattern of eye movement differences between children and skilled adults during reading being identified. Importantly, the developmental changes in eye movement behaviour during reading have been demonstrated to be a consequence of increases in a child's cognitive processing abilities.

Despite the limited number of studies, age related changes in eye movement behaviour are well specified; as children get older, fixation durations decrease, saccadic amplitude increases, number of fixations per sentence decreases, regression rate decreases, and probability of a word being skipped increases (Buswell, 1922; Blythe et al., 2006; Blythe, Liversedge, Joseph, White, & Rayner 2009; Blythe, Häikiö, Bertram, Liversedge, & Hyönä, 2011; Häikiö, Bertram, Hyönä, & Niemi, 2009; Huestegge, Radach, Corbic, & Huestegge, 2009; Joseph, Liversedge, Blythe, White, & Rayner, 2009; McConkie et al., 1991; Rayner, 1986; Taylor, 1965). These studies have suggested that the average fixation duration for children aged six is around 325ms, with an average of 200 fixations per 100 words. By age 12, however, average fixation durations during reading are around 250ms, with around 115 fixations per 100 words (Taylor, 1965; McConkie et al., 1991).

It has also been found that fixation durations are similarly affected by word frequency in both developing and skilled readers, with infrequent words receiving longer fixations than frequent words when embedded in sentences (Blythe et al., 2009; Joseph, Nation, & Liversedge, 2013). Crucially, the finding that lexical variables of words influence fixation durations even at a young age suggests that eye movements during reading are influenced by cognitive processes at all stages of reading development. In addition to this, evidence from the disappearing text paradigm has also suggested that eye movements during reading are under cognitive control in children. Blythe et al. (2009) demonstrated that when children read sentences containing words that disappeared from the screen after 60ms, that they were no more disrupted in terms of speed or comprehension accuracy than during normal reading. Importantly, this lack of disruption has also been observed in adults, suggesting that children require a comparable amount of time to adults to extract visual information during a fixation, but differ in their cognitive processing abilities. The observation of similar phenomena in children and adult readers suggests that the key constant between these groups is the influence of cognitive processes during reading on eye movements.

A critical issue is the development of a child's ability to parafoveally pre-process words in sentences. As mentioned in the prior section, this ability is a vital part of skilled reading, in that pre-processing facilitates lexical identification when a word is directly fixated. A small number of studies have focused upon parafoveal pre-processing in children using both the moving window and boundary paradigms outlined previously. The amount of letter and word length information that can be processed from the parafovea increases with age, as the perceptual span increases both in terms of extent and the type of information that can be extracted from it (Häikiö et al., 2009; Rayner, 1986; Sperlich, Schad, & Laubrock, 2015). The perceptual span of beginning readers is smaller than that of skilled readers, extending around 11 characters to the right of point of fixation in English, and around one year of reading experience is necessary for the span to develop asymmetrically (Rayner, 1986). These developmental changes in the perceptual span suggest that children are less able to extract parafoveal information during reading, and that more cognitive processing resources are required for foveal processing than for skilled adult readers. This demonstrates that information about upcoming letters and words is processed during reading even in developing readers, and that the allocation of attention to parafoveal processing as a reader's cognitive processing ability develops extends the perceptual span.

As mentioned previously, the moving window paradigm has been used to study the extent of the perceptual span, but the boundary paradigm is more useful with regards to the type of information that is parafoveally pre-processed. A recent study investigated the type of information children were able to parafoveally pre-process during reading. Tiffin-Richards and Schroeder (2015) used the boundary paradigm to examine the extent to which children are able to extract phonological and orthographic information from the parafovea compared to skilled adult readers in German. Children (roughly 8 years old) demonstrated shorter single fixations and gaze durations on target words (e.g., *leim*) when previewed by pseudohomophones (e.g., *laim*) compared to control words (e.g., *loim*), whilst adults demonstrated no pseudohomophone effect (that is, no difference between pseudohomophones and control words). It was also found that children did not show an internal transposed letter preview benefit (e.g., shorter fixations when previewing *band* with *bnad*), but this effect was observed in adults. These results suggested that whilst children are able to parafoveally pre-process the phonological characteristics of words, their ability to flexibly encode orthographic information may continue to develop as their experience with print grows.

There is also evidence that very young readers are able to use parafoveal information to target their saccades. McConkie et al. (1991) demonstrated that children target their saccades similarly to adults, with saccades generally landing near to the centre of the word. If saccades are targeted too far to the right, often adults will make a short leftward refixation within the word to correct for this. Both children and adults will refixate in this way, although refixation is a more common occurrence in children (Blythe et al., 2009). The finding that young children and adults target their saccades towards the centre of words suggests that, despite the more limited extent of parafoveal processing discussed above in developing readers, these younger readers were able to parafoveally pre-process words for the purposes of saccadic targeting in the same way as adults.

Findings discussed in this section demonstrate the sensitivity of eye tracking measures to record differences in eye movement behaviour in developing and skilled readers. Changes in eye movement behaviour that occur as reading experience increases reflect developing cognitive processing ability; the typical shortening of fixations and decreases in the number of fixations, regressions and refixations is reflective of developmental changes in cognitive processing ability. The extent to which children are able to parafoveally pre-process words has also been discussed. It would appear that young readers are able to use parafoveal information to target their saccades to word centres, in a similar fashion to skilled adult readers, but that the extent of the perceptual span may be reduced in younger readers (Häikiö et al., 2009; Rayner, 1986; Sperlich et al., 2015). Increases in the ability to parafoveally pre-process words are attributed to cognitive processing ability, allowing children to allocate more attention away from foveal processing. The crucial point to make is that at all stages of reading development, eye movements are under cognitive control- fixations durations are similarly influenced by word frequency in children and skilled adults, and both require a similar amount of time to visually process a word on fixation (Blythe et al., 2009; Joseph et al., 2013). These findings demonstrate that the differences observed between young readers and skilled adults are a result of differing levels of cognitive processing ability.

2.3: Eye Movement Behaviour during Reading in Developmental Dyslexia

As reading skill increases, fixation durations and number of fixations generally decrease, saccade amplitude increases, and regression rate decreases (Rayner, 1998; Blythe et al., 2011). There is, however, evidence to suggest that readers with dyslexia do not progress at the same rate as their typically developing peers, and this reading deficit has been investigated using eye movement measures. Typically, readers with dyslexia have demonstrated longer fixations durations, a greater number of overall fixations, shorter saccadic amplitude, and more regressions than typically developing readers of the same age (Biscaldi, Gezeck, & Stuhr, 1998; Elterman, Abel, Daroff, Dell'Orso, & Bornstein, 1980; Hutzler & Wimmer, 2004; Prado, Dubois, & Valdois, 2007; Rubino & Minden, 1974; see Kirkby, Webster, Blythe, & Liversedge, 2008, for a review).

A key question with regards to the atypical eye movement behaviour associated with dyslexia is the extent to which such behaviour is a cause or consequence of the reading difficulties observed. In section 2.1 the link between eye movement measures and underlying cognitive processes in reading was discussed. This relationship is particularly important when considering the differences in eye movement behaviour between typically developing children and those with dyslexia; it has been suggested that the differing eye movement patterns in children with dyslexia could be due to an underlying visual deficit rather than a specific linguistic disability. Pavlidis (1981) recorded eye movements whilst participants with and without dyslexia fixated a series of LEDs along a horizontal array, finding that fixations on the LEDs were less spatially accurate in participants with dyslexia. Pavlidis (1981) suggested that this finding demonstrated a visual deficit in dyslexia, and not necessarily an underlying deficit in linguistic processing. Subsequent attempts to replicate this study have not, however, yielded the same results (e.g., Olson, Kliegl, & Davidson, 1983; see Kirkby et al., 2008 for a review). A number of researchers have used eye movement tasks that do not involve linguistic processing, but require participants to move their eyes in similar patterns to those observed in normal reading. Hutzler, Kronbichler, Jacobs, and Wimmer (2006) used a task in which participants were required to search through consonant strings for adjacent identical characters- this required a pattern of fixations and saccades similar to reading but did not involve linguistic processing. Hutzler et al. (2006) found no differences in eye movement behaviour between typically developed participants and those with dyslexia, suggesting that any observed differences in eye movement behaviour associated with dyslexia are a consequence of a linguistic processing deficit, and not simply an oculomotor disability. This has been further affirmed by the finding that the eye movements of readers with dyslexia are sensitive to word frequency (Jones, Kelly, & Corley, 2007).

There is also evidence to suggest that the perceptual span and parafoveal processing are impaired in readers with dyslexia. Rayner, Murphy, Henderson, and Pollatsek (1989) used the moving window paradigm, manipulating the size of the window in terms of the number of words visible, testing typically developing children and children with dyslexia. It was found that children with dyslexia showed unimpaired reading in all window size conditions except for the condition in which the window was just one word in size (i.e., when only the currently fixated word was visible). Typically developing children, by contrast, only demonstrated unimpaired reading at a window size of three words. This evidence suggests that children with dyslexia have a reduced capacity for parafoveal pre-processing, perhaps due to a greater allocation of processing resources on the currently fixated word due to linguistic processing difficulties (see also, Chace et al., 2005). As discussed in the previous sections, the pattern of differences in parafoveal pre-processing ability between developing readers and skilled adults is attributed to differences in cognitive processing ability. Children with dyslexia have linguistic processing difficulties that may require more attentional resources to be focused on the foveal word, further reducing their capacity to parafoveally pre-process words.

There have been few studies investigating the processing of phonology during silent sentence reading in readers with dyslexia. One such study was conducted by Jones et al. (2007), investigating whether readers with dyslexia were sensitive to regularity. Adult participants with and without dyslexia read sentences containing phonologically regular and irregular target words, and whilst the typically developing participant group had shorter reading times on regular items compared to irregular items, this difference was not observed in participants with dyslexia. The authors suggested that readers with dyslexia did not parafoveally pre-process the phonological characteristics of upcoming words to the same extent as typically developing readers.

In summary, considerable evidence has demonstrated that children with dyslexia exhibit eye movement behaviour consistently different to that of their typically developing peers. Evidence has implicated linguistic processing difficulties as the cause of this atypical eye movement behaviour, rather than oculomotor deficits (Kirkby et al., 2008). In previous sections, phonological processing abilities have been implicated as an important factor in learning to read and in dyslexia, and the next subsection will discuss the contribution eye movement research has made to this topic. To our knowledge, no research has focused upon using eye movements to investigate phonological processing in typically developing children or children with dyslexia.

2.4: <u>Summary</u>

This focus of this section has been the characteristics of eye movements during reading, and how they differ between various groups of readers. Only a small region of the retina, the fovea, is able to perceive words with high acuity. Retinal distance from the fovea is associated with a decrease in visual acuity, with the parafovea and periphery extending beyond the fovea. The composition of the retina in this way underlies the need to move the eyes during reading in order to perceive printed words with the highest acuity vision possible, and a pattern of saccadic eye movements is necessary to bring new regions of text to the fovea (see Rayner, 1998, 2009, for reviews). There is abundant evidence that eye movements are driven by cognitive processing, and that the characteristics of the text being read influence fixation times and saccade measures. For instance, a frequent or predictable word is typically fixated for a briefer period and skipped more often than an infrequent or unpredictable one (Inhoff & Rayner, 1986; Rayner & Well, 1996). Moreover, the disappearing text paradigm has demonstrated that even when the text being read disappears fairly quickly following fixation onset (60ms), reading can continue relatively undisturbed, and the frequency effect remains intact (Liversedge et al., 2004; Rayner et al., 2006; Rayner et al., 2003). This research demonstrates that linguistic factors predominantly determine when the eyes are moved during reading.

With this in mind, differences between skilled adult and developing readers should be expected in terms of their eye movements during reading, as the latter's linguistic processing ability will not yet have reached adult level. The majority of eye movement research has focused upon reading in skilled adult populations, but more recently children, both typically developing and with dyslexia, have been studied using this methodology. The eye movements of typically developing children are quantitatively different to that of skilled adult readers; younger readers demonstrate longer and more fixations, shorter saccades, more regressions, and fewer instances of word skipping, with age-related changes in these measures occurring. The differences between these two groups in eye movement behaviour during reading is reflective of differences in cognitive processing ability, and improvement in reading ability leads to increases in the amount of information that can be extracted from text per fixation and the extent of the perceptual span (Rayner, 1986), allowing for more information to be extracted from the parafovea. In comparison with typically developing children, children with dyslexia fixate words more and for longer, make shorter saccades and more regressions, and are less likely to skip words. There is also evidence associating dyslexia with a reduced perceptual span and less efficient parafoveal processing compared to typically developing readers (Rayner et al., 1989). This differential pattern of eye movements does not appear to be the cause of the reading difficulties associated with dyslexia, rather a reflection of a linguistic processing deficit in children with dyslexia (Hutzler et al., 2006).

Given the robust link between phonological processing deficits in children with dyslexia (Bradley & Bryant, 1978; Hulme, 1981; Liberman, 1973; Snowling, 1981, 2000; Ramus et al., 2003), and the findings discussed in this section suggesting that phonological characteristics of words influence eye movements, research directly investigating phonological recoding in children with dyslexia is required to further understand how this deficit impacts upon reading. The following sections outline two experiments that aimed to investigate phonological recoding in children both with and without dyslexia, using eye-tracking to provide insight into cognitive processing during reading

Chapter Three: Pre-screening procedures for Experiments One and Two

3.1. Introduction

In the previous chapter, prior research into eye movement behaviour during reading was discussed in depth. Unlike other methodologies discussed so far in this thesis, such as word naming, lexical decision tasks, and semantic categorisation, during eye movement experiments participants read target words that are embedded into full sentences to study cognitive processing under conditions that closely resemble normal silent reading. In order to ensure stimuli are appropriate, pre-screening is typically undertaken to select experimental materials that are suited to the purposes of the experiment. Two pre-screening procedures were run to select final stimuli for Experiments One and Two reported in this thesis.

Comprehension. The first pre-screening procedure was used to ensure that all sentences selected for the final experiments were fully comprehensible to all readers. The use of eye movements as a measure of cognitive processing during reading depends on the reader being able to understand the meaning of the words and sentences being read. If this is not the case, it will become impossible to reliably interpret the observed patterns of eye movement behaviour. If the participant cannot comprehend the sentence, it cannot be known what precisely their eye movement behaviour is reflective of, and eye movement measures in such a scenario will, thus, not be indicative of the cognitive processing that underpins normal reading. This is a particularly important concern in the context of the present studies, in which readers with and without dyslexia were compared in terms of their eye movement behaviour during reading. By design, participants with dyslexia may have more difficulty cognitively processing sentences during reading relative to typically developing readers. In order to make valid group comparisons, and to be able to draw theoretical conclusions with respect to cognitive processing during reading, it is, therefore, vital to ensure that sentences are comprehensible to all readers.

It is difficult, however, to ensure that participants with reading difficulties will understand experimental stimuli prior to their recruitment. Teenage readers were recruited for the two eye movement experiments, to allow a set of participant group comparisons to be made between reading in young readers with and without dyslexia (See Chapter Four for group matching procedures). The youngest readers in the sample would be roughly 13 years old, with some also having dyslexia. This meant that their reading ability could be several years behind that which would be predicted based on their age. In order to ensure that the poorest readers in the sample were able to fully comprehend the reading materials, sentences were pre-screened with younger readers, between the ages of eight and nine. If materials were comprehensible to children reading at the level predicted at this age, it could be ensured that older readers with dyslexia would comprehend them, even given lower reading levels than expected for their age.

Constraint. It was also vital that the final experimental sentences were very highly semantically constraining to their target word. Consider the design of Experiment One (See Chapter 4.2); in this experiment, participants read sentences containing one of three types of target word; a correct target (e.g., *money*), a pseudohomophone (a nonword that shares phonology with a correct target word, e.g., *munni*), or a spelling control word (a nonword that has the same number of different letters to the correct target word as the pseudohomophone, but does not share phonology, e.g., *menro*). Ensuring that sentences are highly constraining to each correct target word is vital because these nonword items may be entirely unrecognisable to readers in sentences that are neutral or not constraining to them. If this was the case, eye movement behaviour whilst reading these sentences may not resemble cognitive processing that typically underpins silent reading, but, rather, may reflect a guessing exercise where participants must effortfully attempt to process each nonword. Alternatively, highly constraining sentences should support the identification of the correct target word from its corresponding nonword, even in cases where the nonword bears little orthographic similarity to it.

To summarise, it was firstly important that all readers in the final sample, both typically developing and with dyslexia, were equally able to comprehend the experimental sentences. If this is not the case, it cannot be known to what extent eye movement behaviour during reading is reflective of cognitive processing. Secondly, it was important that all sentences were highly semantically constraining to their correct target word. Neutral or low constraint sentences may lead to eye movement behaviour that more closely resembles a guessing exercise than normal silent reading, whilst highly constraining sentences will aid identification of the correct target word from each of its nonwords. Two pre-screening procedures were used to address these concerns.

3.2: Method

Participants. Participants were 78 children, between the ages of eight and nine years old. All participants were school children attending one of three local primary schools, and took part on a voluntary basis. These participants had no known reading difficulties, and did not take part in either of the two eye movement experiments.

Materials and design. Initially, 48 triplets were created, each consisting of a correct target word, a pseudohomophone, and a spelling control, and four sentence frames were created for each triplet. Each correct target word was controlled on a number of properties (See Chapter 4.2). First, all were between four and six letters long. Second, age of acquisition for the correct target word was always below seven years old. Third, a pseudohomophone and a pronounceable spelling control could be created from that target word without altering its length. Due to the difficulty in creating triplets of items under these tightly controlled criteria, the same triplets were used in both Experiment One and Experiment Two.

Pre-screening was carried out using more triplets than would be required for the final experiments. During pre-screening, participants never rated target words directly, and never read sentences containing nonword items, but, in this way, the results of the pre-screening determined which target words were included in the final experiments (see Chapter 4.2 and 5.2). Participants similarly rated many more sentence frames than were used in the final experiments. Four sentences were created to accommodate each of the 48 correct target words. As mentioned above, it was anticipated that, for some triplets, one or none of the sentence frames would be rated to the level that would satisfy the criteria for inclusion in the final study. Two sentences were required to be selected for inclusion for each target triplet; one for use in Experiment One, and the other for use in Experiment Two.

Each participant took part in one of two tasks. In one task, they were asked to rate sentences based on how difficult they found them to read and understand. Each participant was presented with sentences and asked to rate each one on a scale of 1 (easy) to 7 (difficult). In the other task, each participant was provided with sentence frames that had a blank space in place of each target word (only one per sentence), and were asked to write a single word in the gap that they thought best fit the sentence context. These two tasks will hereafter be referred to as the sentence comprehension task and sentence constraint task respectively.

Tasks were administered on a class-by-class basis. In order to ensure that these young participants did not tire of the repetitive nature of each task, two subsets of the total list of sentences were created. Instead of reading and rating all 192 sentences for a given task, each participant was presented with a subset of 96 sentences, comprising of two of the four sentence frames for each of the 48 target words. Collecting data from children in class is generally a time sensitive process, and despite this shortening of the total sentences to be rated not all children completed the full task. In order to avoid those sentences that appeared at the end of each subset receiving fewer ratings than those at the beginning due to participants running out of time, each of the two subsets of the sentences were pseudo-randomised differently across three lists for each task (i.e., the content of those three versions of the questionnaire was the same, but the items occurred in a different order). These lists were pseudo-randomised to ensure that the two sentences for any given target word appeared on different pages and were separated by at least 10 other sentences. Furthermore, following this randomisation, any sentences that remained close to the end of all three lists were moved towards the beginning of one of them. Each sentence received ratings from between ten and 16 children across both tasks.

Procedure. Data was collected in the classroom. For each class, the experimenter explained the task, including some instruction on how to rate an example sentence included at the top of each subset of sentences. Participants in a given class were then given hard copies of one of the three lists of sentences (the same items, but in different, pseudo-randomised orders). This was done in such a way that no two participants sitting next to each other were given the same list, to avoid copying. Participants were given a chance to ask questions, and informed that they could raise their hand to ask the experimenter a question during the task. They were also instructed to read a book quietly if they finished the task early. Participants were instructed to read a consent form, and to sign it if they were willing to take part. Following these instructions, participants were given 30 minutes to complete the task in silence.

3.3. Results

Scores from the sentence constraint task for individual sentences ranged from 0%, where no participants selected the intended target word based on its sentential context, to 100%, where all participants selected the intended target word. Individual sentence frames were considered for inclusion if the target word was selected by at least 60% of the participants. Mean scores on the comprehension task ranged from 1.00 to 2.44, demonstrating that the participants found all sentences fairly easy to read. A mean score of 2.00 was selected as the maximum for consideration (recall that this was on a scale from 1, “easy” to 7, “difficult”).

On the basis of these criteria, 24 target words were selected for the eye movement experiments, each with two sentence frames. One sentence frame was used in Experiment One, and the other in Experiment Two. Sentences for Experiment One received a mean rating of 1.39 (range: 1.00-1.87) on the sentence comprehension task, and a mean rating of 94% (range: 80%-100%) in the sentence constraint task. The sentences for Experiment Two received a mean rating of 1.37 (range: 1.06-1.97) in the sentence comprehension task, and a mean rating of 81% (range: 60%-100%) in the sentence constraint task.

3.4: Discussion

Through these pre-screening procedures, 24 target words were selected for use in the final eye movement experiments, each with two sentence frames. It was ensured that all sentences would be comprehensible even to the poorest readers in the final sample of participants. This allowed a valid comparison to be made between groups of readers with and without dyslexia with regard to their cognitive processing during reading. It was also ensured that sentences were highly constraining to their correct target word. This meant that, in instances where participants read nonword items, that identification of the correct target word from its corresponding nonword should be facilitated. These pre-screening procedures provided a set of tightly controlled stimuli for the final two eye movement experiments.

Chapter Four: Experiment One: The role of phonology in lexical identification in teenagers with dyslexia

4.1 Introduction

In Experiment One, the aim was to examine the role of phonological recoding during silent sentence reading in teenagers, both with and without dyslexia. Phonological recoding is an effortless and subconscious process whereby a reader accesses the abstract phonological representation of a word from its orthography (Frost, 1998), and is considered a vital component of lexical identification in skilled adult readers (Rayner, Pollatsek, & Binder, 1998). There is, however, robust evidence that deficits in certain phonological processing abilities are a key factor related to the reading difficulties associated with dyslexia (see Snowling, 2000). It is not precisely understood how these deficits impact upon silent reading, nor how the ability to phonologically recode written words typically develops. In this experiment, eye tracking was used to investigate differences in both phonological and orthographic processing between teenagers with and without dyslexia during silent sentence reading.

One of the most influential theories for the reading difficulties associated with dyslexia is the phonological deficit hypothesis (e.g., Liberman, 1973; Vellutino, 1979; Snowling, 1981). The cornerstone of this theory is that children with dyslexia have fundamental difficulties with the storage and retrieval of the speech sounds associated with words, impacting on their ability to learn grapheme-phoneme correspondences, a vital aspect of reading acquisition (Ramus et al., 2003) and an ability that underpins phonological recoding. Children with dyslexia perform poorly on phonological awareness tasks such as phoneme manipulation (Bradley & Bryant, 1978; Elbro & Jensen, 2005), and have poor verbal short term memory (Snowling, 2000; Szenkovits & Ramus, 2005) as evidenced by poor performance on nonword repetition and digit span tasks. Under the phonological deficit theory, such deficits are the key causal factor leading to the reading difficulties associated with dyslexia (Snowling, 2000; Vellutino, 1979). Alternative theories (e.g., Goswami, 2011; Nicolson & Fawcett, 1990; Stein, 2001) have acknowledged these deficits as a key mediator among various other neurological factors, leading to a widespread concurrence on the importance of phonological deficits in dyslexia. The experimental paradigms described above, however, typically involved additional tasks that are not components of normal silent reading, and it is thus essential to use a research method such as eye tracking to investigate on-going linguistic processing during reading. In such studies, participants are not typically required to pronounce letter strings, or explicitly decide upon their lexical status or semantic category, allowing researchers to investigate the cognitive processes underlying silent sentence reading without extraneous task demands.

The nature of phonological processing during reading was discussed at length in Chapter One. In particular, an important experimental question concerns whether phonological information is processed prior to or following lexical access. If the former is true, phonological information may also influence lexical access itself. Evidence for prelexical phonological processing has been provided by a variety of tasks, such as naming (e.g., Bauer & Stanovich, 1980; Lesch & Pollatsek, 1993; Seidenberg, Waters, Barnes, & Tanenhaus, 1984), lexical decision (e.g., McCann, Besner, & Davelaar, 1988; Meyer, Schvanevedlt, & Ruddy, 1974; Rubenstein, Lewis, & Rubenstein, 1971), and semantic categorisation (Van Orden, 1987; Van Orden, Johnston, & Hale, 1988). The extent to which the extraneous demands of each task influences phonological processing, however, remains unclear (Leinenger, 2014), and the clearest evidence for prelexical phonological processing has been provided by eye tracking studies. It has been unequivocally demonstrated that eye movements are reflective of underlying cognitive processing during reading (Liversedge & Findlay, 2000; Rayner, 1998, 2009), and eye tracking thus serves as a useful methodology for investigating the cognitive processes that underlie silent reading. Studies of this nature have suggested that phonological information is processed prior to lexical access, and in some cases even before a word is directly fixated (Chace, Rayner, & Well, 2005; Miellet & Sparrow, 2004; Pollatsek, Lesch, Morris, & Rayner, 1992; Rayner, Pollatsek, & Binder, 1998), strongly suggesting a vital role for phonological recoding in lexical access in skilled adults readers.

The studies cited above collected data from samples of skilled adult readers to investigate phonological recoding, but a separate empirical issue concerns how younger readers use phonological information during silent reading, and how the ability to phonologically recode words during reading typically develops. Decoding is the effortful sublexical process whereby a reader, either overtly through pronunciation or by reciting mentally, sounds out the constituent phonological units of a word. With increased reading experience, however, this practice of sounding out words becomes unnecessarily laborious, and readers transition to whole word processing through either orthographic processing or phonological recoding. A recent study by Blythe, Pagán, and Dodd (2015) investigated the transition from decoding to recoding by comparing the eye movements of young readers (aged 7 to 9) with those of skilled adults. Blythe et al. (2015) used correct target words, pseudohomophones (nonwords that shared phonology with a correct target word), and spelling control words (nonwords that did not share phonology with a correct target word) as stimuli. Young children and adults demonstrated a remarkably similar sensitivity to phonology; both groups showed a pseudohomophone advantage (decreased reading times on pseudohomophones compared to spelling controls), suggesting that children as young as seven years old may have already developed sophisticated phonological processing, comparable to skilled adult readers. If the younger group were using decoding strategies to read nonwords, far longer reading times would have been observed on these items than correct target words, reflecting the time-consuming nature of overt decoding. This did not appear to be the case, however, and this study provided evidence for phonological recoding in relatively young readers.

Less, however, is known about how children with dyslexia transition from decoding to recoding. It may be the case that, in dyslexia, the transition from effortful decoding to more automatic recoding simply does not occur within the same time frame as in typically developing readers. If this view of a developmental delay were correct, then readers with dyslexia would, with continued reading instruction, transition to more sophisticated recoding, albeit at a later stage than their typically developing peers. Alternatively, there could be a developmental deficit that fundamentally affects decoding ability and prevents the transition to phonological recoding, leaving readers with dyslexia to instead rely on the orthographic characteristics of words to aid lexical identification. Differentiating between these two possibilities- delayed versus atypical development- is crucial when comparing readers with and without dyslexia, and the experiment described in this chapter was designed in a way that allowed the investigation of each. The use of teenage readers in this study, rather than younger children with dyslexia, allowed a detailed set of comparisons to be made that investigated both atypical and delayed development associated with dyslexia. Previous studies have investigated eye movements during reading in younger children, but none to date have investigated the intervening developmental period during the teenage years, wherein a reader increases their experience with printed words and lexical representations become more fully specified.

As discussed, eye-tracking has previously been useful in understanding the nature of phonological recoding in skilled adults. Despite the greater volume of eye movement studies conducted using adult readers compared to equivalent research with developing readers, the overall pattern of differences between these populations has recently become fairly well specified in terms of eye movement behaviour during reading. As children get older and continue to receive reading instruction, fixations decrease in both duration and quantity, saccades increase in length, regressions become less frequent and word skipping increases (see Blythe & Joseph, 2011, for a review). Rather than reflecting more accurate or efficient oculomotor control, these eye movement changes are associated with developing cognitive processing abilities as children continue to improve in reading ability (Rayner, 1986). In a study by Reichle et al. (2013), the E-Z Reader model of eye movement control was used to simulate some of the eye movement differences between children and adults in reading. These simulations demonstrated that the main determinant of age-related differences in eye movement behaviour during reading was the rate of lexical processing, rather than any oculomotor factors. These results suggest that as children continue to develop their reading ability, changes in eye movement behaviour during reading are determined by their ability to lexically process the text.

Similarly, differences in cognitive processing ability are reflected in the eye movement behaviour of readers with and without dyslexia, with the former exhibiting longer and more fixations, more regressions, and shorter saccades than typically developing children (see Kirkby, Webster, Blythe, & Liversedge, 2008; Rayner, 1985, for reviews). Specifically, the eye movement behaviour of children with dyslexia, and the way in which it differs from typically developing children, is widely accepted as a consequence rather than a cause of the reading difficulties associated with dyslexia

(Hutzler, Kronbichler, Jacobs, & Wimmer, 2006; Rayner, 1985). Whilst, therefore, the basic pattern of differences in eye movement behaviour between children and adults is well specified, less is understood about how children make the transition from overt and effortful decoding to more automatic recoding, and how this transition is affected by dyslexia.

In addition to the investigation of atypical versus delayed development as described above, the use of teenage participants in this study is motivated by three additional factors. Firstly, as children continue to receive formal reading instruction and their experience with print increases, they develop automatic phonological recoding rather than requiring effortful decoding strategies whilst reading to identify words (Share, 1995). Secondly, increased reading experience also helps to develop children’s lexical representations to become more fully specified, a process that continues throughout secondary education. As children continue to develop their reading ability, the orthographic, phonological, and semantic information relating to a lexical entry becomes better specified. This process continues throughout secondary education, and it is, thus, of interest to study teenage readers with regards to their reading development. Finally, another motivation for studying teenage readers with dyslexia regards the long-term nature of the associated reading difficulties. Adult participants with dyslexia have shown similar patterns of reading difficulties to those observed in younger readers (Bruck, 1992), suggesting that any reading difficulties experienced in childhood can last beyond the point at which readers cease to receive reading instruction. As discussed in Chapter 1, the ability to learn and understand the mappings between graphemes and phonemes is vital to successful reading acquisition, and research of this nature strongly suggests that difficulties in acquiring this ability are fundamentally detrimental to learning to read. The influence of dyslexia, therefore, does not end in childhood, and it is important to study children, teenagers and young adults with dyslexia to more widely understand reading development and the impact of early reading difficulties on later reading proficiency.

In addition to differences between groups of readers, it may also be the case that orthographic features of words themselves may modulate any differences in phonological recoding ability observed between children with and without dyslexia. For instance, children with dyslexia typically perform more poorly than typically developing children on phonological decoding tasks using pseudowords. A pseudoword is a pronounceable nonword (e.g., *tidding*), and in such tasks participants are required to pronounce these letter strings as if they were real words. A number of studies have shown that children with dyslexia are impaired at this task (Grainger, Bouttevin, Truc, Bastien, & Ziegler, 2003; Wimmer, 1993), with the explanation for this pattern being that children with dyslexia have poorly specified phonological representations of words, a cornerstone of the phonological deficit hypothesis of dyslexia (Snowling, 2000). It may then be that children with dyslexia are overly reliant on the orthographic characteristics of words and nonwords, and that the degree of orthographic overlap between a pseudoword and similar lexical entries influences the facility with which a participant is able to pronounce that pseudoword. A critical issue is, thus, whether deficits in phonological recoding observed in dyslexia are modulated by the degree of orthographic similarity between nonwords and real words, and the relationship between phonological and orthographic characteristics of words will be investigated in this study.

In the interest of studying differences in both phonological and orthographic processing between groups of readers with and without dyslexia, four participant groups were recruited for the following experiment. Firstly, a group of teenagers with dyslexia, aged between 16 and 18, was recruited. As mentioned, prior research on dyslexia has typically been focused upon younger readers or adults, and the aim in recruiting this age group was to address the intervening period of reading development, in which children are 'reading to learn' (Chall, 1983). All participants in this group had received an independent diagnosis of dyslexia. Secondly, a typically developing group of teenagers matched on chronological age to the group with dyslexia was recruited. These two groups of teenagers had spent an equivalent period of time in formal education but had not attained the same level of reading expertise, and their comparison allowed investigation of the developmental delays in eye movement behaviour and phonological processing during reading associated with dyslexia.

Used in isolation, however, this chronological age-matched comparison presents a major methodological issue, in that any observed group differences may not be a consequence of a core deficit associated with dyslexia, but may simply be a product of the different reading abilities between groups (Backman, Mamen, & Ferguson, 1984, though see Bryant & Goswami, 1986). In order to address this, a group of typically developing children who were matched to the group with dyslexia on reading ability was recruited. Any differences observed between the group with dyslexia and this reading-ability matched control group cannot, therefore, be attributed to lower reading ability but may instead reflect a deficit specific to dyslexia. Similarly, if differences are observed between chronological-age matched children with and without dyslexia, but not between reading-level matched children, then it may be the case that the group with dyslexia are simply delayed compared to their typically developing peers, and that if they were to reach the equivalent reading level, then such differences may not be observed. The use of both a chronological age-matched comparison and a reading level-matched comparison in this study will allow the investigation of atypical versus delayed development, and will reduce any ambiguity regarding the pattern of results that is obtained.

This reading-ability matched typically developing group additionally served as a chronological age-matched group for a second, younger, participant group with dyslexia. This fourth group was again comprised of individuals who had each received an independent diagnosis of dyslexia, and allowed a second chronological age-matched comparison to be made. Contrasting differences in eye movement behaviour between typically developing readers and readers with dyslexia at two separate points in reading development will allow for a broader investigation of the development of cognitive processing abilities in dyslexia. In addition to comparisons of readers with and without dyslexia, this design also allowed for a fourth comparison to be drawn, between older and younger typically developing teenagers, and older and younger teenagers with dyslexia. These comparisons allowed investigation of differences in phonological processing based on chronological age, and how those developmental changes may be affected by dyslexia. In this way, these four groups allowed a series of theoretically motivated comparisons to be made between teenagers both with and without dyslexia with regards to the development of both phonological and orthographic processing.

In order to make this series of comparisons, it was vital to collect extensive additional data from our participants to facilitate reliable group matching. All participants were assessed on their word reading ability, the purpose of which was twofold. Firstly, this allowed for confirmation that the participants with dyslexia were indeed impaired in their reading, and, conversely, that no reading difficulties were present in the typically developing groups. This is a nontrivial issue as the interpretation of results, and the validity of our planned comparisons, depends entirely on this difference in reading ability between teenagers with and without dyslexia being observed. Secondly, the collection of reading ability data allowed the recruitment of the group of typically developing readers who were matched to the dyslexia group on reading level, facilitating this comparison and allowing a more detailed investigation into the deficits associated with dyslexia, rather than areas in which teenagers with dyslexia may simply be delayed in their development. Participants were also tested on their ability to pronounce nonwords (pseudoword decoding). Prior research has shown that participants with dyslexia are impaired on this task compared to typically developing readers (Grainger, Bouttevin, Truc, Bastien, & Ziegler, 2003; Wimmer, 1993), due to the phonological processing deficits associated with dyslexia. As this task concerns decoding only, however, it is not informative with regards to how children with dyslexia phonologically recode stimuli. The use of eye-tracking allows investigation of the covert, instantaneous process whereby readers phonologically recode words to access their abstract phonological characteristics.

Previous evidence has also suggested that readers with dyslexia have impaired vocabulary and phonological awareness compared to typically developing readers (Snowling, Gallagher, & Frith, 2003, see Snowling, 2000, for a review). All participants were thus tested on their vocabulary and their ability to complete two simple tasks manipulating the spoken forms of words and nonwords, to further verify the basis of our group comparisons, and to better understand the nature of the reading deficits associated with dyslexia. As mentioned previously, robust difficulties in phonological processing ability have been observed in children with dyslexia, and the observation of difficulties in our groups with dyslexia would further confirm that these groups indeed did have dyslexia, rather than a more general reading deficit. Nonverbal IQ was also assessed, to ensure that there were no differences in general intelligence between the four participant groups. Whilst general intelligence is no longer considered within the diagnosis of dyslexia (American Psychiatric Association, 2013), it was important to ensure that any reading difficulties observed could not be attributed to a lower than average IQ. A detailed outline of each of the specific pen and paper assessment tasks and the group matching procedures will be given in the Method section.

With respect to the eye tracking experiment, each participant silently read sentences containing one of three types of target word/nonword whilst their eye movements were tracked. The phonological and orthographic characteristics of the target word were manipulated such that participants read a sentence containing either a correct target word (e.g., *cheese*), a pseudohomophone (a nonword that shared phonology with the correct target but differed in its orthography, e.g., *cheeze*), or a spelling control (a nonword that differed in both phonology and orthography from the correct target, e.g., *cheene*). The degree of orthographic overlap within each correct word/pseudohomophone/spelling control was also varied; half of all triplets of targets were classed as orthographically similar (e.g., *cheese/cheeze/cheene*), with only one letter altered, and half were classed as orthographically dissimilar (e.g., *crane/krane/drauv*), with two or more letters altered.

A number of specific hypotheses were made regarding both global eye movement behaviour between groups and the effect of the target word manipulations. Firstly, global eye movement differences were predicted between our participants with and without dyslexia. Children with dyslexia typically exhibit longer and more fixations, more regressions, shorter saccades, and a longer overall reading times, compared to those without dyslexia, and it was predicted that each of our two chronological age-matched comparisons of teenagers with and without dyslexia would produce robust effects consistent with this pattern. In addition to this, a similar pattern of global eye movement differences was predicted between the older group with dyslexia, and the typically developing group matched on reading ability. Previous research has demonstrated that children with dyslexia have significantly poorer performance in reading related tasks compared to typically developing children at the equivalent reading level, but no eye movement studies to date have used a reading level-matched design to investigate cognitive processing in dyslexia. Finally with regards to global group effects, it was predicted that a significant overall effect of age would emerge- the two groups of older participants would demonstrate shorter and fewer fixations, fewer regressions, increased word skipping, and faster overall reading times compared to the two groups of younger participants, in line with previous research on the concurrent development of cognitive processing abilities and eye movements during reading (e.g., see Blythe & Joseph, 2011, for a review).

Regarding the influence of the target word manipulations upon eye movement behaviour, four hypotheses were made. Firstly, a significant effect of orthographic similarity would be observed, such that shorter reading times would be observed on nonwords that were orthographically similar to their correctly spelled base word (e.g., *cheese/cheeze/cheene*) than on nonwords that were orthographically dissimilar (e.g., *crane/krane/drauv*). As mentioned earlier, a word may be identified based on its phonological and orthographic characteristics, and thus a greater degree of orthographic overlap to facilitate identification of the base word from its misspelled form would be expected. It was also predicted that orthographic similarity would interact with group; due to the phonological processing deficits associated with dyslexia, it may be the case that these readers rely more on orthographic processing to identify words than their typically developing peers. The predicted pattern of results would, therefore, be a greater cost in terms of reading times for all groups with dyslexia on items in orthographically dissimilar conditions compared to orthographically similar conditions. Secondly, a significant effect of phonological condition was predicted, such that the shortest reading times would be observed on correct target words, and the longest reading times would be observed on spelling control nonwords. Correct target words should receive the shortest fixation times by virtue of being an accurate representation of a lexical entry. Pseudohomophones should receive shorter reading times than spelling control nonwords due to the shared phonology with a lexical entry. Shorter reading times on phonologically correct nonwords compared to phonologically incorrect nonwords (spelling controls) would suggest that the phonological recoding aided the identification of the correct target word associated with the nonword, and this effect will hereafter be referred to as a pseudohomophone advantage. There is, however, a great deal of evidence to suggest that readers with dyslexia have difficulties in processing the phonological characteristics of words. Our third hypothesis was, therefore, that that the groups with dyslexia would demonstrate no pseudohomophone advantage, in contrast to both their chronologically age-matched and reading level-matched typically developing peers. This effect was predicted in all groups in which readers with and without dyslexia were compared, due to the specific phonological processing deficits associated with dyslexia.

The fourth hypothesis concerned age-related differences in phonological and orthographic processing. Our careful selection of groups additionally allowed for comparisons to be made between children, both with and without dyslexia, at different stages of reading development in their teenage years. Concerning the comparison of the two typically developing groups, an interaction with phonological condition was predicted, such that a greater pseudohomophone advantage would occur in the older group. Through greater reading experience, older teenage readers may have more fully specified cognitive representations of words in terms of their phonological and orthographic constituents, which will facilitate faster lexical identification than in the younger groups. The older group may thus be more efficient at accessing the lexical entry that corresponds to a pseudohomophone than their younger peers. In the case of the two groups with dyslexia, this developmental increase in the pseudohomophone advantage was not predicted. It was predicted that neither of these groups would demonstrate a significant pseudohomophone advantage, given the reading difficulties associated with dyslexia and their prevalence throughout and beyond the process of receiving formal reading instruction.

4.2: Method

Participants. Participants were older typically developing teenagers (TDO), older teenagers with dyslexia (DO), younger typically developing teenagers matched to the dyslexia group on reading skill (TDY), and younger teenagers with dyslexia matched to the younger typically developing group on chronological age (DY; see Table 4.1). All had English as their first language, and all had normal or corrected-to-normal vision. All participants within the dyslexia groups had received an independent diagnosis of dyslexia. Furthermore, as described in the Introduction, all participants were tested on their reading ability as part of this study. The collection of this data, as described below, had two vital purposes. Firstly, providing confirmation that each group with dyslexia was significantly impaired in word reading ability compared to the typically developing groups, thus supporting their diagnosis and affirming the validity of the intended comparisons. Secondly, the word reading scores obtained by the groups with dyslexia allowed and mean reading age to be calculated, and this reading age formed the basis for the recruitment of the reading-ability matched group.

Participants were also tested on their nonverbal IQ, to ensure that any reading difficulties observed were not conflated with general intelligence differences, and their vocabulary and phonological processing, to establish the pattern of reading difficulties across groups and measure phonological processing in tasks that were independent of the eye tracking experiment. Means and standard deviations from each of these assessments by group can be seen in Table 4.1.

Materials.

Reading ability. Wechsler Individual Achievement Test (WIAT-II). Participants completed two subtests of the WIAT-II (Weschler, 2005). The word reading subtest is a measure of single word reading using phonologically regular and irregular words. The pseudoword decoding subtest is a single nonword reading measure using pronounceable nonwords. These subtests provided reading accuracy raw scores, which reflected the number of words or nonwords read correctly, and which were then converted to age-equivalent standardised scores.

Table 4.1. Participant group means and standard deviations and pen and paper results.

	TDO	DO	TDY	DY
N	30	22	26	10
Age, in months	207 (5)	207 (14)	178 (5)	175 (8)
Age range	193 – 216	185 - 245	168 – 185	156 - 183
Word reading SS[a]	109 (6.09)	96 (7.78)	101 (10.2)	88 (14.36)
Word reading raw[a]	125 (3.22)	118 (4.22)	120 (5.77)	111 (8.16)
Pseudoword decoding[a]	103 (7.43)	88 (12.13)	99 (9.71)	85 (8.61)
IQ[b]	90 (14.82)	93 (9.12)	93 (16.04)	91 (15.82)
Vocabulary[c]	105 (7.49)	101 (9.55)	100 (8.77)	98 (9.69)
Phon. processing[d]	96 (12.96)	90 (9.61)	94 (12.95)	92 (17.27)

Note. Standard deviations in parentheses. [a]WIAT-II subtests, SS= standardised scores, [b]RPM standardised scores; [c]BPVS standardised scores; [d]CTOPP sum of subtest standardised scores. TDO = older typically developing group, DO = older group with dyslexia, TDY = younger typically developing group, DY = younger group with dyslexia.

Phonological processing. Comprehensive Test of Phonological Processing (CTOPP). Participants completed two subtests of the CTOPP (Wagner, Torgesen, & Rashotte, 1999). The elision subtest measured the ability to remove phonological segments from spoken words to form new words. In the blending words subtest, the ability to combine individual sounds to form words was assessed. These subtests provided raw scores for each participant, which were standardised and summed to give an overall score for phonological awareness.

Vocabulary: British Picture Vocabulary Scale (BPVS; Dunn, Dunn, Styles, & Sewell, 2009). A vocabulary assessment test that places minimal demands on reading and is, thus, ideally suited for administering to readers with dyslexia; on each trial, the experimenter read a single word aloud, and the participant was presented with four pictures and asked to indicate, either verbally or by gesturing, which picture best illustrated that word's meaning. This test provided raw scores, which were then standardised.

IQ: Ravens Progressive Matrices (RPM; Raven, Court, & Raven, 1998). A multiple choice measure of non-verbal general intelligence. Participants were required to identify the missing element that completed a pattern from a series of either six or eight possible answers, and were given 20 minutes to complete as many items as possible. Forty minutes is the standard assessment time for this measure, but participants were given a shorter administration time in the present study in order to complete all assessments in one session. The shorter administration time means that the raw scores systematically underestimate IQ, such that standardised scores could not be interpreted as an estimate of IQ in relation to the broader population. They remain, however, useful for the purpose of group matching, as all participants received the same administration time.

Group matching procedure. The collection of the assessment data described above formed the basis of the group matching procedure. As described in the Introduction, there were four key group comparisons to be made. There were no significant differences in nonverbal IQ between any groups (all $ts < 1.71$, all $ps > .1$).

Comparison One: Older teenagers with dyslexia and older typically developing teenagers. Each of these two groups had received equivalent reading instruction; however, the group with dyslexia had not obtained the same level of reading ability. The first criterion essential for this comparison was that there could be no significant group differences in chronological age. A mean age was obtained from the older group with dyslexia, and from this a group of typically developing older teenagers was constructed from a larger sample of typically developing readers, with no significant differences observed in chronological age ($t(50) = .13$, $p = .89$). This latter group of 30 typically developing readers was selected after testing 33 participants in total to form the matched samples. The second criterion for this comparison concerned reading ability. It was vital that significant differences in word reading ability were observed between the typically developing groups and the groups with dyslexia, as previously explained. Standardised scores from the word reading subtest of the WIAT-II were used- the standardised score transforms the raw score to give a reading ability in relation to what would be considered ‘average’ for a reader’s age. The lack of difference in chronological age between the groups thus makes the use of the standardised score in this regard valid. There were significant differences in word reading and pseudoword decoding standardised scores, and vocabulary, between these groups (all ts(50) >2, all ps < .05), and no significant difference in phonological processing ($t(50) = 1.61$, $p = .11$).

Comparison Two: Older teenagers with dyslexia and a younger typically developing teenagers, matched on reading ability. The first criterion essential for this comparison was that no significant differences were observed in reading ability, showing that each group has attained an equivalent level of reading expertise, despite one group receiving more years of formal reading instruction. Raw scores, rather than standardised scores, were used for this comparison. Because standardised scores give a score based on what is considered typical for an age group, it is inappropriate to match groups based on standardised scores, which will be inherently low in the group with dyslexia. In order for them to be considered typically developing, this group must have reading ability consistent with their age group. Raw scores were thus used for this comparison. There were significant differences in chronological age between the older group with dyslexia and the younger typically developing group ($t(47) = 10.4$, $p < .001$), and no significant differences in word reading ability ($t(47) = 1.61$, $p = .12$). There was however a significant difference in pseudoword decoding between groups ($t(47) = 3.56$, $p = <.01$). No significant differences were observed in vocabulary or phonological processing (both $ts(47) < 1.16$, both $ps > .25$) Again, an initial, larger, sample of 29 younger typically developing participants was carefully trimmed to leave a final sample of 26 readers that satisfied these criteria.

Comparison Three: Younger typically developing teenagers and younger teenagers with dyslexia. This comparison is conceptually identical to the first comparison, but using younger participants. Any differences observed between groups in the first comparison can be contrasted with those observed in this third comparison, to investigate the development of the reading difficulties associated with dyslexia and how these differences develop over time. The younger group with dyslexia was matched to the younger typically developing group on chronological age ($t(34) = 1.48$, $p = .15$), but were significantly poorer readers as measured by standardised scores from the word reading subtest of the WIAT-II ($t(34) = 2.78$, $p = <.01$). There were also significant group differences in pseudoword decoding ($t(34) = 3.89$, $p = >.001$), but no significant differences in vocabulary or phonological processing (both $ts(34) < 0.67$, both $ps > .75$). A larger sample of 14 younger readers with dyslexia was trimmed to leave a final sample of 10.

Comparison Four: Older and younger typically developing teenagers, and older and younger teenagers with dyslexia. As mentioned, differences in eye movement behaviour between children and adults are well specified, but less is known about the development of cognitive processing during the teenage years. Similarly, developments in eye movement behaviour throughout the teenage years in dyslexia can be studied, and in particular aspects of eye movement behaviour during reading that may continue to develop in spite of the reading difficulties associated with dyslexia. There was a significant difference in chronological age between each of the older and younger groups (both *t*s(54)> 7.04, *p*s <.001). The older and younger typically developing groups significantly differed in their word reading and vocabulary (all *ts*(54) > 2.4, all *ps* < .02), with no significant differences in phonological processing (*t*(54)= .42, *p* = .67). The older and younger groups with dyslexia did not significantly differ in their word reading, pseudoword decoding, phonological processing, and or (all *ts*(30) < 1.5, all *ps* >.24).

Apparatus. An EyeLink 2K eye tracker (SR Research, Toronto, Canada) was used to record monocular eye movements from the right eye, although viewing was binocular. The position of the participant's eye was recorded every millisecond. Sentences were presented on a 19" Viewsonic CRT monitor operating at 100Hz (120Hz for one participant) at a viewing distance of 60 cm. Sentences were presented in black, Courier New font size 14 on a grey background. Courier New font (a monospaced font) was used to ensure that each individual letter comprised the same width on the monitor. Participants leaned on a chinrest and a forehead rest during the experiment to keep head movements to a minimum, and used a Microsoft gamepad to answer comprehension questions and target test questions, and to terminate each sentence.

Stimuli and design. Twenty-four triplets of target words/nonwords were created. Each triplet was comprised of a correctly spelled word, a pseudohomophone of that target word, and a spelling control nonword. The 24 correctly spelled target words were those selected from the pre-screening procedures outlined in Chapter 3. All triplets were comprised of words/nonwords of equivalent word length, and all items were between 4-6 letters long. The spelling control nonword was created by mirroring the orthographic change between the correctly spelled word and the pseudohomophone, to create a nonword that did not share phonology with the correct target word. Correct target words were between four and six letters long, with a range of child and adult frequencies (child frequency range = 8-560 per million, adult frequency range = 1824-246556 per million). Pseudohomophones and orthographic control words always shared the same word length, number of syllables, consonant-vowel structure, and patterns of ascending and descending letters as their corresponding correct words, and orthographic control words were always orthographically legal and pronounceable. Target words/nonwords were inserted into sentences selected from the pre-screening procedures outlined in Chapter Three

Twenty one of these triplets were classed as orthographically similar, where the nonword differed from the correct target word on just one letter, which was never the first or second letter (e.g., *cheese*/*cheeze*/*cheene*). The remaining 27 triplets were classed as orthographically dissimilar in that two or three letters were changed from the correct word, and the initial letter was never preserved (e.g., *crane*/k*rain*/*drauv*). The two lists of correct target words were matched on number of orthographic neighbours (the number of words that could be created by changing a single letter in the target word), adult frequency, and child frequency (all *ts* <2, all *ps* >.1). There were slight differences in word length between orthographically similar triplets (mean length = 5.33 letters) and dissimilar triplets (mean length = 4.67 letters; t = 2.1, p = .05).

In the eye-tracking study, each participant read the same 24 sentence frames in a randomised order, with the target word or nonword rotated across three counterbalanced files. Each participant thus read eight sentences containing correct target words, eight containing pseudohomophones, and eight containing orthographic spelling controls. A simple comprehension question followed 25% of sentences, requiring a yes or no response using the button pad, to ensure participants were reading the sentences for meaning. It was considered important that participants were able to identify what the target word was meant to be from the sentence context, given the orthographic and phonological differences between correct target words and orthographic control words. To account for this, a ‘target test’ question was also included after roughly 50% of the trials in which participants read a pseudohomophone or a control word. Participants were reminded that a word had been spelled incorrectly in the immediately preceding trial, and were given two options as to what the incorrectly spelt word should have been. The two options were the correct target word (e.g., *leader*) and a distractor word matched on both length and on the number of letter changes between the correct word and the target nonword in the sentence (e.g., *ladder*). Distractor items were also matched on child and adult frequency to the correct target words. After any given sentence, participants were only asked one of the two types of question.

Procedure. Participants were seated, and were asked to make themselves comfortable. They were instructed to read silently for meaning, and to expect questions relating to the sentence they had just read. Participants were given a gamepad to hold during the experiment. By pressing either of the shoulder buttons, participants could indicate that they had finished reading each sentence, thus terminating each trial, and answer questions as they appeared. A calibration procedure was then completed; participants were required to fixate three stationary dots as they sequentially appeared across a horizontal array. Eye positions were recorded for each of the three fixation points, followed by an identical three-point accuracy validation. If the mean gaze-position error between the initial calibration and the validation was greater than 0.2^{o} averaged across calibration points or for any one of the three calibration points individually, the calibration and validation procedure was repeated. Following an accurate calibration, the presentation of stimuli began. On each trial, participants fixated a central cross, followed by a gaze-contingent cross on the left of the screen, which triggered the appearance of the sentence when fixated. This ensured that the first fixation on each trial was at the beginning of the sentence. When necessary, calibration was repeated between trials, and the experiment resumed where it had been interrupted. Participants read four practice sentences: two were followed by comprehension questions; the other two were followed by target tests. Following the completion of the eye movement experiment, participants completed the pen and paper assessments in a variable order.

4.3. Results

The results from this study are split into global and local eye movement analyses. Global analyses of eye movements focus upon cognitive processing over the entire sentence, and measures such as mean fixation duration and number of fixations can be used to compare participant groups with regards to their overall reading behaviour. Local analyses, by contrast, focus upon cognitive processing of the target word or nonword within each sentence only. The use of a combination of dependent measures in local analyses relating to first and second pass reading gives information around the time course of word identification. The unbalanced design of this experiment warranted a two-step approach to be taken to local eye movement analyses. Despite being matched on a variety of variables, there was no meaningful comparison to be made between correct target words based on which orthographic similarity category they were in, as orthographic similarity referred to the relationship between a correct target and its two misspelled partners within each triplet. The results were, therefore, firstly collapsed across orthographic similarity, and reading times on each type of nonwords (orthographically similar and dissimilar pseudohomophones and orthographically similar and dissimilar spelling controls) were compared to correctly spelled words. This analysis will be referred to as Model 1, and allows examination of the cost associated with processing nonwords. In Model 2, correctly spelled words were excluded from the analysis altogether; reading times on pseudohomophones and spelling controls only were compared to examine the effects of the experimental manipulations in a balanced design.

Fixations were cleaned in four distinct stages using the clean function in the EyeLink Dataviewer software (SR Research, Ontario, Canada). In the first two stages, fixations shorter than 80ms were merged with the neighbouring fixation if within a 0.5^{o} distance of another fixation over 80ms, and fixations shorter than 40ms were merged with neighbouring fixations if within a 1.25^{o} distance of another fixation. In the third stage, individual interest areas were checked and if an interest area had three or more fixations shorter than 80ms, these were merged into a single, longer, fixation. In the final stage, all remaining fixations that were shorter than 80ms or longer than 1200ms were deleted. A number of global and local eye movement measures were selected to investigate differences between our groups. These measures were analysed using the lme4 package (Bates, Maechler, Bolker, & Walker, 2014) within the R environment for statistical computing (R Core Development Team, 2014) with linear mixed effects models (LME models). All models contained participants and target words/nonwords as random factors, with the full random structure where possible. Where models failed to converge, the random structure of each model was pruned until the model converged. All fixation duration measures were log-transformed in order to reduce distributional skewing (Baayen, Davidson, & Bates, 2008). Effects were estimated using the lmer function of the lme4 package, with regression coefficients (b), standard errors (SE) and t values reported in Table 3. For the word skipping analyses logistic linear mixed models were implemented, and z statistics from these analyses are reported. Following common practice, the significance level for t and z values was 1.96.

Table 4.2. Means and standard deviations for global eye movement measures.

	TRT	Fix Count	MFD	Skip	Reg Count
TD Older	3745	15.79	231	0.41	4.05
	(1174)	(4.63)	(109)		(2.58)
D Older	5316	19.87	254	0.33	4.9
	(1857)	(5.89)	(131)		(2.71)
TD Younger	4290	16.6	254	0.38	4.05
	(1648)	(5.3)	(124)		(2.57)
D Younger	6512	23.3	261	0.29	5.63
	(3733)	(9.54)	(136)		(3.67)

Note. Standard deviations in parentheses. TRT = total reading time, in milliseconds; Fix Count = fixation count, in mean number of fixations per sentence; MFD = mean fixation duration, in milliseconds; Skip = probability of words being skipped during first pass reading; Reg Count = regression count, in mean number of regressions per sentences.

Global eye movement results. The means and standard deviations for global measures of eye movement behaviour between groups can be observed in Table 4.2, and fixed effects estimates are shown in Table 4.3. The model syntax for global measures was dependent variable ~ group + (1|participant) + (1+group|triplet number). All models were run using the sdif function to compare conditions successively, rather than iteratively to an intercept condition. Comparisons between older and younger groups of participants are denoted under age-related contrasts in Tables 4.3 and 4.6. A number of measures were investigated: total sentence reading time (the mean duration between the first fixation on the sentence and the button press that indicated the participant had finished reading), the mean number of fixations per sentence, the mean number of regressions per sentence, mean fixation duration (the mean length of a fixation during reading), and word skipping probability (the likelihood that a word was skipped during first pass reading). A number of global eye movement differences were predicted between groups.

Firstly, differences in eye movement behaviour were predicted between teenagers with and without dyslexia. The four participant groups were designed to investigate this in two ways; through two comparisons of teenagers with and without dyslexia, matched for chronological age (older and younger, and through a comparison of teenagers with dyslexia and younger typically developing readers who were matched on reading ability. The two chronological age-matched comparisons yielded similar results; participants with dyslexia had significantly longer sentence reading times, made significantly more fixations per sentence than their typically developing peers, and were less likely to skip words during reading. Older participants with dyslexia also had significantly longer fixation durations than their typically developing counterparts, and younger participants with dyslexia made more regressions per sentence than their typically developing peers. No difference in the number of regressions per sentence was observed between the two older chronological age-matched groups, nor was a difference observed in mean fixation duration between the two younger chronological age-matched groups. These age-matched comparisons provide strong evidence for greater cognitive processing difficulty during reading in teenagers with dyslexia relative to typically developing teenagers.

It could, however, be the case that readers with dyslexia found these sentences more difficult due to their relative lack of skill and experience with printed text, as opposed to being the consequence of a cognitive processing deficit specific to reading

(Backman et al., 1984, though see Bryant & Goswami, 1986). The reading ability-matched comparison showed differences in eye movement behaviour that suggested atypical, rather than delayed, development in the teenagers with dyslexia. Participants with dyslexia had longer sentence reading times, made more fixations per sentence, and were less likely to skip words than typically developing readers at an equivalent reading level. The fact that consistent global eye movement differences emerged in both the chronological age-matched and the reading level-matched comparisons strongly suggests that the eye movement behaviour observed in the readers with dyslexia is not solely a result of lower reading level or lack of experience with printed text, but, instead, reflects atypical development.

Secondly, age-related developments in eye movement behaviour were predicted. Specifically, it was predicted that younger readers, both typically developing and with dyslexia, would demonstrate a different pattern of eye movement behaviour relative to older readers; specifically, longer and more fixations, shorter saccades, fewer instances of word skipping, and more regressions, reflecting better developed lexical processing consistent with prior research (Reichle et al., 2013). Younger typically developing participants had longer mean fixation durations than older typically developing children and younger children with dyslexia made more fixations per sentence than older children with dyslexia. Whilst age-related differences were not observed across all dependant measures, previous research has suggested that a child's eye movements are becoming adult-like by age 12 (Blythe et al., 2009, 2011, Rayner, 1986). On the basis of the current study it may be the case that certain aspects of eye movement behaviour continue to develop past this age, as teenagers continue to develop better reading skills and more efficient lexical processing. The regression coefficients, standard errors, and t values of these analysis can be seen in Table 4.3, under age related contrasts.

In summary, differences in global eye movement behaviour between groups of readers with and without dyslexia have been clearly demonstrated. As predicted, readers with dyslexia demonstrated a pattern consistent with prior research; significantly longer total sentence reading times and more fixations per sentence were observed in the groups with dyslexia across both chronological age-matched comparisons. In the reading level-matched comparison, readers with dyslexia again had significantly longer total sentence reading times and made more fixations than their typically developing peers. This is the first study to use a reading ability-matched design to investigate cognitive processing during reading in dyslexia. The presence of group differences across each type of comparison suggests that readers with dyslexia are not simply delayed in their development; when compared to typically developing readers at an equivalent reading age, a similar pattern of differences is observed. This suggests that the basis of this difference may be in atypical development in the groups with dyslexia rather than delayed development.

Table 4.3. Fixed effects estimates for global measures of eye movements

	Total reading time			Fixation count			Mean fixation duration		
	b	SE	t	b	SE	t	b	SE	t
Intercept (grand mean)	8.42	0.04	239.36	18.9	0.6	33.17	5.43	0.01	437.30
Group (TDO vs. DO)	0.34	0.07	5.07	4.08	1.07	3.80	0.08	0.03	2.90
Group (DO vs. TDY)	-0.23	0.07	3.28	-3.27	1.11	2.92	0.00	0.03	0.10
Group (TDY vs. DY)	0.38	0.09	4.21	6.72	1.47	4.78	0.02	0.04	0.40
Age-related contrasts									
Group (TDO vs. TDY)	0.11	0.06	1.73	0.81	1.01	0.8	0.08	0.03	2.9
Group (DO vs. DY)	0.15	0.23	1.6	3.45	1.44	2.39	0.02	0.04	0.5

	Skip				Regression count		
	b	SE	z	p	b	SE	t
Intercept (grand mean)	-0.64	0.05	13.04	<.001	4.66	0.25	18.44
Group (TDO vs. DO)	-0.37	0.09	4.1	<.001	0.85	0.50	1.7
Group (DO vs. TDY)	0.25	0.09	2.76	<.01	-0.85	0.52	1.64
Group (TDY vs. DY)	-0.45	0.12	3.71	<.001	1.58	0.67	2.34
Age-related contrasts							
Group (TDO vs. TDY)	0.11	0.08	1.29	.19	0.005	0.47	0.01
Group (DO vs. DY)	-0.02	0.12	1.58	.11	0.73	0.69	1.07

Note. TDO = Older typically developing group; DO = Older group with dyslexia; TDY = younger typically developing group; DY = younger group with dyslexia t or z values above 1.96 indicate statistically significant difference. SE = standard error.

Local eye movement analyses. The means and standard deviations for local measures of eye movement behaviour between groups can be observed in Table 4.44, and fixed effects estimates are shown in Table 3. Local eye movement measures concern reading times on the target word or nonword in the sentence only, and it is in these measures that the independent variables of phonological condition and orthographic similarity were investigated. Local measures included single fixation duration (the duration of the first fixation on a word or nonword when it was the only first pass fixation during reading), first fixation duration (the duration of the first fixation on a word or nonword regardless of whether it was fixated again in first pass reading), gaze duration (the summed duration of all first pass fixations on a word or nonword), and total fixation time (the summed duration of all fixations on a word or nonword). The probability of participants making a single fixation on the target word or nonword was as follows for each group: 0.64 for the older typically developing group, 0.61 for the older group with dyslexia, 0.68 for the younger typically developing group, and 0.53 for the younger group with dyslexia.

Recall that two separate analyses were conducted. The first (Model 1) collapsed correct target words across orthographic similarity, comparing them with each type of misspelled word. The second (Model 2) removed correct target words entirely, and focused upon differences in reading times between pseudohomophones and spelling controls. These analyses will be described in turn.

Model 1. This analysis was conducted in order to make a comparison between correctly spelled target words (e.g., summer/circle), and each of the four types of misspelled words that participants were presented with: 1) Orthographically similar pseudohomophones (e.g., *summur*); 2) Orthographically dissimilar pseudohomophones (e.g., *sercle*); 3) Orthographically similar spelling controls (e.g., *summor*); 4)

Orthographically dissimilar spelling controls (e.g., *norcle*). An LME model was constructed with group and target type as fixed factors with an interaction between the two (dependent variable ~ group*target type + (1+group*target type|participant) + (1+group*target type|triplet number).

Table 4.4. Means for local eye movement measures.

		TDO		DO		TDY		DY	
		Orth. similar	Orth. dissimilar	Orth. similar	Orth. dissimilar	Orth. similar	Orth. dissimilar	Orth. similar	Orth. dissimilar
SFD	Correct targets	205	221	229	213	210	232	243	261
	Pseudohomophones	226	282	259	326	266	285	237	314
	Spelling Controls	264	285	244	362	287	313	338	329
FFD	Correct targets	199	218	234	214	212	230	250	251
	Pseudohomophones	224	270	262	298	255	280	239	290
	Spelling Controls	255	280	281	343	283	303	320	282
GD	Correct targets	223	265	275	280	239	251	339	308
	Pseudohomophones	318	349	378	469	358	382	477	483
	Spelling Controls	368	417	454	568	396	478	489	661
TT	Correct targets	267	293	307	396	297	314	465	426
	Pseudohomophones	582	543	826	847	626	653	774	916
	Spelling Controls	592	744	904	1217	726	947	871	1369

Note. TDO = Older typically developing group; DO = Older group with dyslexia; TDY = younger typically developing group; DY = younger group with dyslexia. SFD = single fixation duration, in milliseconds; FFD = first fixation duration, in milliseconds; GD = gaze duration, in milliseconds, TT = total fixation time, in milliseconds.

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Table 4.5. Fixed effects estimates for Model 1 analyses

Term No.		Single fixation duration			First fixation duration			Gaze duration			Total time		
		b	SE	t	b	SE	t	b	SE	t	b	SE	t
	Intercept (TDO, Correct)	4.54	0.07	65.21	4.50	0.06	72.12	5.09	0.06	83.05	5.65	0.07	80.91
1	Target (OS P)	0.13	0.10	1.34	0.13	0.08	1.60	0.29	0.09	3.27	0.57	0.07	8.71
2	Target (OD P)	0.38	0.10	3.82	0.38	0.08	4.72	0.39	0.09	4.45	0.48	0.06	7.45
3	Target (OS S)	0.40	0.10	3.96	0.32	0.08	3.98	0.50	0.09	5.75	0.64	0.07	9.81
4	Target (OD S)	0.35	0.10	3.47	0.40	0.08	4.93	0.44	0.09	5.06	0.78	0.07	11.99
5	Group (DO)	0.18	0.10	1.86	0.21	0.09	2.33	0.20	0.09	2.28	0.15	0.09	1.69
6	Group (TDY)	0.13	0.09	1.40	0.17	0.09	1.96	0.06	0.08	0.78	0.01	0.08	0.12
7	Group (DY)	0.24	0.13	1.91	0.27	0.11	2.36	0.30	0.11	2.80	0.33	0.12	2.86
8	Group x Target (DO, OS P)	-0.06	0.15	0.44	0.00	0.12	0.01	-0.16	0.13	1.23	0.06	0.10	0.67
9	Group x Target (DO, OD P)	-0.12	0.15	0.78	-0.16	0.12	1.32	-0.09	0.13	0.73	0.30	0.10	3.14
10	Group x Target (DO, OS S)	-0.33	0.15	2.21	-0.12	0.12	0.97	-0.34	0.13	2.65	0.18	0.10	1.87
11	Group x Target (DO, OD S)	-0.03	0.15	0.21	-0.03	0.12	0.22	-0.27	0.13	2.10	0.34	0.10	3.53
12	Group x Target (TDY, OS P)	0.01	0.14	0.10	-0.04	0.12	0.35	-0.07	0.12	0.55	0.06	0.09	0.61
13	Group x Target (TDY, OD P)	-0.11	0.14	0.82	-0.13	0.11	1.09	-0.05	0.12	0.44	0.15	0.09	1.63
14	Group x Target (TDY, OS S)	-0.07	0.14	0.48	0.02	0.12	0.18	-0.19	0.12	1.55	0.16	0.09	1.76
15	Group x Target (TDY, OD S)	0.01	0.14	0.05	-0.06	0.12	0.54	-0.05	0.12	0.38	0.27	0.09	3.00
16	Group x Target (DY, OS P)	-0.10	0.21	0.45	-0.11	0.15	0.74	-0.11	0.16	0.66	-0.10	0.12	0.80
17	Group x Target (DY, OD P)	-0.09	0.19	0.46	-0.15	0.15	0.98	-0.37	0.16	2.32	0.19	0.12	1.56
18	Group x Target (DY, OS S)	0.07	0.19	0.38	0.07	0.15	0.46	-0.33	0.16	2.07	-0.01	0.12	0.11
19	Group x Target (DY, OD S)	-0.19	0.20	0.93	-0.42	0.15	2.80	-0.55	0.16	3.41	0.20	0.12	1.61

Note. TDO = Older typically developing group; DO = Older group with dyslexia; TDY = younger typically developing group; DY = younger group with dyslexia, OS = orthographically similar, OD = orthographically dissimilar. P = pseudohomophone, S = spelling control. t or z values above 1.96 indicate statistically significant difference to intercept. SE = standard error.

Table 4.6. Fixed effects estimates for Model 2 analyses.

Term No		Single fixation duration			First fixation duration			Gaze duration			Total time		
		b	SE	t	b	SE	t	b	SE	t	b	SE	t
	Main model												
	Intercept (grand mean)	5.56	0.03	212.99	5.53	0.02	257.37	5.88	0.04	134.28	6.50	0.05	124.72
1	Group (TDO vs. DO)	0.09	0.06	1.41	0.12	0.05	2.22	0.20	0.07	2.95	0.37	0.09	4.22
2	Group (D vs. TDY)	-0.02	0.06	0.25	-0.03	0.05	0.66	-0.10	0.07	1.50	-0.20	0.09	2.28
3	Group (TDY vs. DY)	0.06	0.08	0.74	0.01	0.06	0.08	0.22	0.09	2.34	0.23	0.11	2.03
4	Phon	0.08	0.04	1.86	0.08	0.03	2.73	0.14	0.05	2.69	0.25	0.05	4.68
5	Orth	0.11	0.04	2.81	0.08	0.03	2.44	0.14	0.08	1.85	0.20	0.08	2.43
6	Group x Phon (TDO vs. DO)	-0.03	0.08	0.39	0.02	0.06	0.39	0.03	0.08	0.31	0.08	0.08	1.02
7	Group x Phon (DO vs. TDY)	0.03	0.09	0.32	-0.01	0.06	0.17	-0.02	0.08	0.24	0.03	0.08	0.36
8	Group x Phon (TDY vs. DY)	0.06	0.12	0.55	0.00	0.08	0.01	-0.02	0.10	0.19	-0.06	0.10	0.60
9	Group x Orth (TDO vs. DO)	0.16	0.10	1.66	0.01	0.08	0.14	0.14	0.08	1.67	0.20	0.09	2.17
10	Group x Orth (DO vs. TDY)	-0.21	0.09	2.37	-0.08	0.07	1.06	-0.12	0.09	1.35	-0.10	0.09	1.10
11	Group x Orth (TDY vs. DY)	-0.01	0.11	0.11	-0.06	0.09	0.71	0.02	0.13	0.12	0.15	0.11	1.37
12	Phon x Orth	-0.10	0.08	1.21	-0.11	0.06	1.96	0.00	0.10	0.01	0.19	0.10	1.85
13	Group x Phon x Orth (TDO vs. DO)	0.24	0.15	1.55	0.15	0.12	1.26	0.05	0.16	0.30	-0.08	0.15	0.52
14	Group x Phon x Orth (DO vs. TDY)	-0.09	0.15	0.59	-0.10	0.12	0.83	0.07	0.16	0.47	0.10	0.15	0.68
15	Group x Phon x Orth (TDY vs. DY)	-0.27	0.21	1.28	-0.28	0.15	1.88	-0.02	0.20	0.09	-0.09	0.20	0.47
	Age-related contrasts												
16	Group (TDO vs. TDY)	0.07	0.05	1.38	0.09	0.05	1.84	0.09	0.06	1.45	0.17	0.08	2.06
17	Group (DO vs. DY)	0.04	0.09	0.49	-0.03	0.07	0.40	0.12	0.09	1.29	0.03	0.12	0.25
18	Group x Phon (TDO vs. TDY)	-0.01	0.08	0.07	0.01	0.06	0.23	0.01	0.08	0.09	0.11	0.07	1.51
19	Group x Phon (DO vs. DY)	0.09	0.12	0.76	-0.01	0.08	0.12	-0.03	0.11	0.31	-0.03	0.10	0.33
20	Group x Orth (TDO vs. TDY)	-0.05	0.07	0.74	-0.07	0.06	1.17	0.01	0.08	0.19	0.10	0.08	1.31
21	Group x Orth (DO vs. DY)	-0.23	0.13	1.72	-0.14	0.10	1.36	-0.11	0.12	0.95	0.05	0.11	0.43
22	Group x Phon x Orth (TDO vs. TDY)	0.15	0.14	1.03	0.05	0.11	0.43	0.12	0.15	0.81	0.03	0.15	0.21
23	Group x Phon x Orth (DO vs. DY)	-0.36	0.22	1.65	-0.38	0.15	2.45	0.05	0.21	0.25	0.00	0.21	0.02

Model 2. Following the analyses with Model 1, correct target words were excluded from Model 2, allowing investigation of differences in reading times between pseudohomophones and spelling controls only. The analyses for Model 2 relate to the orthogonal manipulations of phonological condition (pseduohomophones versus spelling controls) and orthographic similarity (orthographically similar versus dissimilar) across the four participant groups (older typically developing, older with dyslexia, younger typically developing, younger with dyslexia). These three variables were entered as interacting factors into LME models, with participant and target triplet as random factors. The syntax for the model with the full random structure was dependent variable ~ phoncond*orthcond*group + (1+phoncond*orthcond|participant) + (1+phoncond*group|triplet number). The sdif function was used to compare conditions successively, rather than iteratively to a single intercept condition. LME models were run for the same four dependent eye movement variables; single fixation duration, first fixation duration, gaze duration, and total fixation time. Means for these measures can be seen in Table 4.4, and fixed effects estimates can be seen in Table 4.6. A number of specific hypotheses were made regarding these factors, and these will be evaluated in turn.

Participant group: Two hypotheses were made concerning participant group. Longer overall reading times for groups of readers with dyslexia were predicted compared to the typically developing groups. This pattern was predicted across the two chronological age-matched comparisons and the reading level-matched comparison. Consistent with this prediction, the older group with dyslexia had significantly longer first fixation durations, gaze durations, and total fixation times than the older typically developing group (Term 1 in Table 4.5). The same pattern was observed between the younger typically developing group and younger group with dyslexia in gaze duration and total fixation time (Term 3 in Table 4.5). Concerning the reading level-matched comparison, the older group with dyslexia demonstrated significantly shorter total fixation times than the younger typically developing group (Term 2 in Table 4.5). Distinct differences in eye movement behaviour were observed between the older group with dyslexia and both the older and younger typically developing groups, suggesting a fundamental deficit that impairs cognitive processing of printed text in dyslexia.

The second hypothesis relating to participant group concerned age-related changes in eye movement behaviour. By comparing older with younger typically developing readers, and older with younger readers with dyslexia, it was predicted that older readers would demonstrate shorter reading times than their younger peers. Older typically developing readers made marginally shorter first fixations than younger readers, and this effect was significant in total fixation time, demonstrating age-related differences in cognitive processing during silent reading (Term 16 in Table 4.5). This is consistent with the finding that younger typically developing readers made longer mean fixations than older typically developing readers as reported in the global analyses. Age-related differences between groups of readers with dyslexia were not observed (Term 17 in Table 4.5).

Orthographic similarity. The degree of orthographic overlap between correct target words and their misspelled triplet partners may facilitate lexical identification. Shorter reading times were predicted, therefore, for nonwords that were orthographically similar to their base word. This effect was observed across all local measures except for gaze duration (Term 5 in Table 4.5).

An interaction was also predicted with group; due to the presence of phonological processing deficits, it may be the case that readers with dyslexia have a compensatory reliance on orthography to identify a word, and may demonstrate an even greater benefit for items in the orthographically similar condition than typically developing readers. A marginal group by orthographic similarity interaction was observed for the older typically developing group and older group with dyslexia comparison in single fixation duration that was significant in total fixation time (Term 9 in Table 4.5). A significant group by orthographic similarity interaction was observed in the reading level-matched comparison in single fixation duration only (Term 10 in Table 4.5). Single fixation probability on the target nonword was 0.68 for the older typically developing group and 0.61 for the older group with dyslexia. Although this effect was not observed across all local measures, these results stem from reading times on over 50% of trials. These results suggest that, when compared to the older typically developing group, the older group with dyslexia were more greatly affected when there was a reduced degree of orthographic overlap between a misspelled word and its base correct target (a 92ms differences compared to a 21ms difference in the older typically developing group).

There was also a marginal interaction between group and orthographic similarity in the older and younger dyslexia group comparison in single fixation duration (Term 21 in Table 4.5). Contrasts were run to compare reading times on orthographically similar nonwords and orthographically dissimilar nonwords for the older and younger groups with dyslexia, and revealed significantly longer reading times on orthographically dissimilar items in the older group with dyslexia only (t = 4.1).

In summary, there was a significant cost in terms of reading times on items in orthographically similar conditions compared to dissimilar conditions. A number of interactions were also observed. These interactions involved the older group with dyslexia, and specifically showed that participants in this group had a greater cost than all other participant groups when reading items in orthographically dissimilar conditions.

Phonological condition. The final factor in the manipulation was phonological condition, comparing pseudohomophones and spelling controls. A pseudohomophone advantage would provide evidence for phonological recoding of the misspelled word, and a number of hypotheses concerned this manipulation. Firstly, an overall effect of phonological condition was predicted, specifically that shorter reading times would be observed on pseudohomophones than on spelling controls. This effect was significant for first fixation duration, gaze duration, and total fixation time, and marginal for single fixation duration (Term 4 in Table 4.5); across participant groups, a pseudohomophone advantage was robustly observed.

Secondly, a group by phonological condition interaction was predicted; the pseudohomophone advantage should only be observed in the older and younger typically developing groups, due to the phonological processing deficits associated with dyslexia. An interaction was also predicted between the older and younger groups, reflecting an age-related difference in whether participants demonstrated a pseudohomophone advantage. Across all comparisons, chronological age-matched, reading level-matched, and chronological age-mismatched, no interactions between group and phonological condition were observed in any local measure (Terms 6, 7, 8, 18, and 19 in Table 4.5). All participants demonstrated a robust pseudohomophone advantage, regardless of group. This lack of interaction very strongly suggests that all participant groups were similarly able to benefit from the correct phonology of pseudohomophone targets, despite the presence of reading difficulties in the groups with dyslexia.

Finally, there was a significant phonological condition by orthographic similarity interaction in first fixation duration that was marginal in total fixation time, and contrasts were run to explore this interaction term. Reading times on orthographically similar and orthographically dissimilar pseudohomophones and spelling controls were compared. It was found that the pseudohomophone advantage was present in the orthographically similar conditions only (t = 2.1).

In summary, a robust pseudohomophone advantage was observed. Participants demonstrated shorter reading times on pseudohomophones relative to spelling controls. This effect was observed across all four participant groups, suggesting that this sample of readers, both typically developing and with dyslexia, were phonologically recoding stimuli during silent reading. There was also an interaction between phonological condition and orthographic similarity, and further contrasts revealed that the pseudohomophone effect was significant in orthographically similar items only.

4.4. Discussion

Summary. The aim in this study was to investigate phonological recoding during silent sentence reading in groups of teenagers with and without dyslexia. The way in which readers process phonology and orthography was studied through the use of nonwords (pseudohomophones and spelling controls) that were orthographically similar or dissimilar to their base word. Whether there was differential phonological or orthographic processing during lexical identification in teenagers with dyslexia was studied through the careful matching of four participants groups.

Relating to overall reading behaviour, a number of global eye movement differences between groups of readers with and without dyslexia were observed. Across a number of comparisons, teenagers with dyslexia had significantly longer total sentence reading times and made more fixations per sentence. This consistent pattern of group differences across both types of comparison strongly suggests that readers with dyslexia are atypical in their cognitive processing during reading, rather than simply demonstrating a developmental delay. Younger typically developing readers made more fixations and had longer mean fixation durations than older typically developing readers, and younger teenagers with dyslexia made more fixations per sentence than the older group with dyslexia.

Local analyses comparing reading times on pseudohomophones and spelling controls only were also conducted (Model 2). Focusing first on participant group differences, teenagers with dyslexia had consistently longer reading times than their typically developing peers, across all comparisons. These findings are similar to those observed in both the global eye movement analyses and the analyses from Model 1 concerning group differences. It was also found that older typically developing teenagers had marginally shorter first fixations and significantly shorter total fixation times than younger typically developing teenagers.

An overall effect of orthographic similarity was found, with longer reading times observed on items in the orthographically dissimilar condition than the orthographically similar condition. Interactions with group were also observed, and further contrasts revealed that older readers with dyslexia demonstrated longer reading times on orthographically dissimilar items only. There was also a significant overall effect of phonological condition, indicating a pseudohomophone advantage. Shorter reading times were consistently observed on pseudohomophones compared to spelling controls. Given the phonological processing deficits associated with dyslexia, it was predicted that this advantage would not be observed in the groups with dyslexia. Perhaps the most striking result, then, is the complete lack of group by phonological condition interactions for any local measure. All teenage readers, whether older, younger, typically developing or with dyslexia, were able to phonologically recode the pseudohomophones to access the abstract phonological representation of that pseudohomophone's base correct target word.

Developmental changes in eye movement behaviour during reading. Prior research has demonstrated robust differences between developing and skilled adult readers (see Blythe & Joseph, 2011, for a review) in terms of eye movement behaviour during reading. This pattern of differences is thought to be a result of developing efficiency in the cognitive processes underlying reading, rather than the development of oculomotor control (Reichle et al., 2013). In the present study, it was found that a group of younger teenage readers, with a mean age of 14 years 10 months, had longer mean fixation durations than an older group of typically developing teenagers, with a mean age of 17 years 3 months. In terms of local eye movement measures, younger readers had marginally longer first fixation durations, and significantly longer total fixation times. Additionally, when comparing an older group with dyslexia to a younger group with dyslexia, the latter group made more fixations per sentence. Whilst these groups did not differ significantly across all global and local eye movement measures, it is clear that there were differences between groups in terms of cognitive processing during silent reading.

These results run counter to certain prior findings on eye movement behaviour in children and adults. Rayner (1986) aimed to investigate the development of the perceptual span (the region from which useful information can be obtained during a fixation in reading), comparing groups of younger readers with skilled adults. Rayner (1986) additionally reported global eye movement measures from each group, including mean fixation duration, saccade length, fixation count and regression count per sentence, finding age-related changes between seven and twelve years of age in all measures when participants read full unmasked sentences. In contrasts between the two oldest groups (11-12 years of age and skilled adults), there appeared to only be a small difference in mean fixation duration (5ms) and saccadic amplitude (0.2 characters) between groups. More recently, however, and using a larger sample, Blythe et al. (2011) demonstrated differences in total sentence reading time, mean fixation duration, fixation count and regression count per sentence, and skipping probability during silent sentence reading between groups of ten to eleven year old readers and skilled adults. This more recent study suggests that differences in global eye movement behaviour remain between readers of age 11 and 12 and skilled adults, but the intervening period of reading development has not, to date, been directly investigated using eye movement techniques. The results from the present study suggest that cognitive processing during reading continues to develop throughout the teenage years, as teenagers gain more experience with printed text.

These findings can be related to the lexical quality hypothesis (Perfetti & Hart, 2002); as readers continue their exposure to print, they develop a more fully specified representation of the relationship between the phonological, orthographic, and semantic constituents of words. There is recent evidence to suggest that eye movements are finely tuned to the richness of readers' lexical representations; Luke, Henderson, and Ferreira (2015) demonstrated that the quality of adult participants' representations, as measured by tests of lexical quality, were predictive of a number of eye movement measures during silent reading. It may be the case that continued exposure to the orthographic and phonological forms of words throughout the teenage years allows these constituents to become better specified and facilitate faster lexical identification, reflected by shorter mean fixation durations in the older typically developing teenage group. This explanation remains speculative, however, as whilst the older and younger typically developing groups in the present study were matched on vocabulary size, there was no direct assessment of lexical quality.

Atypical versus delayed development in dyslexia. A central question with regards to the interpretation of these results concerns the basis of eye movement differences observed between groups of readers with and without dyslexia. It may be the case that readers with dyslexia are delayed in some form of their development, and any differences observed with typically developing readers of the same age may be due to their lower reading ability. If this were the case, readers with dyslexia would be able to 'catch up' with their typically developing peers with continued print exposure. It may alternatively be the case that readers with dyslexia are atypical with regards to their cognitive development, and any differences observed with typically developing readers will persist regardless of reading experience. The participant groups in the present experiment were designed to allow for each of these patterns to be tested. Differences were observed in total sentence reading time and number of fixations per sentence across both chronological age-matched comparisons and the reading level-matched comparison. As the first study investigating eye movements in dyslexia to use both types of comparisons, these results strongly suggest a deficit in dyslexia that specifically impairs the development of cognitive processing during reading. This finding is in line with previous theories of dyslexia, such as the phonological deficit hypothesis, which suggest a fundamental deficit rather than a developmental delay in dyslexia (e.g., Liberman, 1973; Vellutino, 1979; Snowling, 1981; Stanovich, 1988).

The pseudohomophone advantage. Recall that a pseudohomophone advantage was predicted in typically developing readers; shorter reading times on pseudohomophones relative to spelling controls, reflecting successful phonological recoding of the former that activated the corresponding lexical entry. This pattern was not, however, predicted in the groups with dyslexia, given the phonological processing deficits thought to be a key causal factor for the associated reading difficulties. Surprisingly, a pseudohomophone advantage was observed across all participants, with no group interactions emerging. In order to account for this, the distinction between phonological decoding and recoding must be considered.

Phonological decoding refers to the effortful, overt process of sounding out words during reading. Such a process is essential during early reading, when the ability to identify written words relies on sublexical processes rather than the whole-word recognition approach that emerges as lexical representations of words become better specified (Ehri, 2005). This latter stage includes phonological recoding, whereby readers are able to quickly and effortlessly access the abstract phonological representations of words. As discussed, prior research has demonstrated that young typically developing readers aged between seven and nine already appeared to be relatively sophisticated with regards to their phonological recoding during silent reading (Blythe, Pagán, & Dodd, 2015). Little, however, is known about how this transition from decoding to recoding may occur in readers with dyslexia. In this study, both older and younger teenagers with dyslexia appeared to phonologically recode stimuli, in a way that did not differ significantly from their typically developing peers, matched on either age or reading level.

Consider the alternatives to the lexical processing that teenage readers with dyslexia might undertake, and how these different underlying processes might be observed in their eye movement behaviour. First, if teenagers with dyslexia were more reliant on decoding during reading, it could be predicted that a pseudohomophone effect would be observed, but that reading times on both pseudohomophones and spelling controls would be significantly longer than those observed in the typically developing groups, due to the slow and effortful strategies that are involved in decoding written letter strings. More specifically, reading times on these items should reflect the time taken to sound out the 4-6 letters of each target nonwords covertly, given the silent nature of the task. Gaze durations between 300-600ms were observed on such items, which are inconsistent with such effortful decoding. Second, if teenagers with dyslexia do not process the phonology of words whatsoever during silent reading, longer reading times would be observed on pseudohomophones and spelling controls than correct target words, with no pseudohomophone advantage. That is, there should be no difference in reading times on these two types of nonwords, which only differed in their phonological overlap with the correct target word. Third, if teenagers with dyslexia were undertaking phonological recoding during lexical identification, then a pseudohomophone advantage would be observed in the absence of the grossly inflated reading times associated with effortful decoding. This final pattern was observed; readers with dyslexia demonstrated a clear benefit for pseudohomophones relative to spelling controls across eye movement measures, and the cost for these two types of nonwords was similar to that observed in typically developing readers. This finding, therefore, strongly suggests that readers with dyslexia are not decoding letter strings, instead relying on more sophisticated phonological recoding.

The finding that teenagers with dyslexia do not differ significantly to their typically developing peers with regards to phonological recoding during silent reading must be considered in the context of the pattern of results from the pen and paper assessments. There were also no significant differences between typically developing teenagers and teenagers with dyslexia in phonological processing ability (CTOPP), a surprising finding given the phonological processing difficulties usually associated with dyslexia. The lack of differences observed between groups in terms of phonological processing as measured by the CTOPP is consistent with findings from the sentence reading study. No group differences were observed in phonological processing as measured by an elision task and a blending words task between groups of readers with and without dyslexia, although the difference was marginally significant in Comparison One, between the older groups with and without dyslexia. Differences were also observed across all four group comparisons in pseudoword decoding, the ability to correctly pronounce an unfamiliar nonword (WIAT-II). These findings demonstrate that, when compared to typically developing readers at both an equivalent age and reading level, teenagers with dyslexia are impaired in their ability to phonologically decode nonword items. Poor performance in the decoding task but not in the silent reading task or the phonological processing task was a surprising finding that may be related to several aspects of the tasks themselves.

Firstly, when teenagers with dyslexia read a pseudohomophone during the sentence reading task, there was a lexical entry that each pseudohomophone corresponded to. It may be the case that correspondence to a lexical entry aided phonological recoding of the pseudohomophone, in a way that was not possible in the pseudoword decoding task, where items do not have this correspondence. Secondly, sentence context may have aided identification in the sentence reading task. Some pseudohomophones and spelling controls, particularly in orthographically dissimilar conditions, bore little resemblance to the lexical entry to which they corresponded (e.g., *honey/hunni/henma*). In order to avoid confusion during the sentence reading task, whereby participants were forced to resort to guessing what each misspelled word should be, each sentence was designed to be highly semantically constraining to the correct target word. It may be that these highly constraining sentences provided some activation for the lexical entry (e.g., *honey*), reducing the difficulty in integrating the orthographically dissimilar spelling control (e.g., *henma*) into the sentence context. It has been demonstrated that words that are highly predictable from the prior sentence context receive shorter fixations during silent reading than words that are not (Ehrlich and Rayner, 1981; Rayner & Well, 1996), indicating that supporting sentence context can facilitate lexical identification of a word. The use of highly predictable sentences in this experiment may have significantly aided identification of the correct target word from its equivalent nonwords. This effect of predictability, however, did not fully override lexical processing, as a pseudohomophone advantage was still observed. This suggests that readers were still phonologically recoding nonwords items, and the aiding sentence context alone was not sufficient to identify the corresponding target word from its equivalent nonwords.

In conclusion, the present study found no evidence for differential phonological processing in teenagers with dyslexia compared to their typically developing peers. All four participant groups demonstrated a cost in terms of fixation durations whilst reading a spelling control compared to a pseudohomophone, despite the fact that readers with dyslexia performed significantly more poorly in a general reading task (the word reading subtest of the WIAT-II) and a pseudoword decoding task. These results, therefore, strongly suggest that teenagers with dyslexia are able to access the abstract phonological representation of words and nonwords during silent sentence reading in a similar way to their typically developing peers, despite the phonological processing deficits widely associated with dyslexia, and despite the pen and paper results from the present study that demonstrated both a lower reading ability and poorer phonological decoding in the groups with dyslexia compared to their typically developing peers. These results do not contradict the phonological deficit hypothesis (Liberman, 1973; Vellutino, 1979; Snowling, 1981; Stanovich, 1988); the readers with dyslexia in the present study were clearly impaired in terms of pseudoword decoding, suggesting less efficient phonological processing. It may the case that the absence of supporting sentence context and a corresponding lexical entry in the pseudoword decoding task meant that readers with dyslexia performed more poorly than their typically developing peers. In the sentence reading task, however, identification of the correct target word from its equivalent nonword was facilitated by both a highly constraining sentence context and the correspondence to a correct target word. Crucially, though, a pseudohomophone advantage was still observed, suggesting phonological recoding in addition to the facilitation provided by predictability.

Orthographic processing in dyslexia. An overall effect of orthographic similarity was observed, such that items in the orthographically similar conditions received shorter fixations than items in orthographically dissimilar conditions. It appears that the degree of orthographic overlap between a misspelled word and its corresponding lexical entry influences the ease with which that word can be identified. It was predicted that participants with dyslexia may be more sensitive to orthography than typically developing readers, with an overreliance on orthographic processing due to their weaker phonological processing during reading.

Unlike in the phonological condition manipulation, there was a trend towards differential orthographic processing in groups with dyslexia compared to their typically developing peers. It is important to note that in all four participant groups, across all four local measures, reading times on items in orthographically similar conditions were shorter than reading times for items in orthographically dissimilar conditions, suggesting an overall cost for reading times on orthographically dissimilar items. The older group with dyslexia in particular, however, demonstrated a much greater cost in reading times on orthographically dissimilar items, with significantly longer single fixation and gaze durations observed on orthographically dissimilar items in the older group with dyslexia only. This can be further observed in the means of the local eye movement measures (Table 4.4). In single fixation duration the older group with dyslexia demonstrated a 56ms cost whilst reading items in orthographically dissimilar conditions (a 31ms cost in the older typically developing group, a 22ms cost in the younger typically developing group, and a 29ms cost in the younger group with dyslexia). A similar pattern was also observed in gaze duration.

On the basis of these findings, it would appear that the older group with dyslexia may be more heavily reliant on orthographic processing during silent reading than their typically developing peers, matched for both chronological age and reading ability. The presence of a nonword item that is orthographically dissimilar to its base correct target word is more detrimental in terms of reading time, as orthographic processing is degraded more than on items in orthographically similar conditions. There were trends towards this pattern in all groups, but the finding that the cost to the older group with dyslexia was significantly greater suggests differential orthographic processing in this group. Interestingly, this pattern was not observed in the younger group with dyslexia, and there was no evidence to suggest differential orthographic processing between the younger group with dyslexia and the younger typically developing group, who were matched on chronological age. This may suggest that as teenagers with dyslexia get older and continue to develop reading experience, they become more reliant on orthographic processing, whereas this reliance does not develop in typically developing readers, and may not yet be present in readers with dyslexia at an earlier stage of reading development. It is, however, important to acknowledge the alternative possibility that this effect was not observed in the younger group with dyslexia due to the smaller sample size. If a significant cost for orthographically dissimilar items was observed with a larger sample in the younger group with dyslexia, it may suggest that teenagers with dyslexia process orthography differently at an even earlier stage of reading development.

Considering these findings together with those from the phonological manipulation, there was some evidence to suggest that the pseudohomophone advantage was greater for items in orthographically similar than dissimilar conditions (33ms versus 21ms, respectively). This finding demonstrates the importance of both orthographic and phonological processing in word identification. Recall that there were no significant differences observed in single and first fixation duration between correct target words and orthographically similar pseudohomophones. These items shared phonology, and differed only by one letter in their orthography. In the case of orthographically similar spelling controls, which also differed by just one letter from correct target words but did not share phonology, a significant difference was observed in all measures of reading time with correct target words. It may be the case that lexical identification can occur in a relatively normal time frame when phonological and orthographic overlap is substantial between correctly spelled and misspelled items. When orthographic and phonological overlap is further reduced however, it may not be the case that this further reduction proportionately slows lexical identification. This would explain why the cost in terms of reading times on orthographically similar spelling controls over pseudohomophones is greater than the equivalent cost for orthographically dissimilar items.

Conclusion. Robust group differences were observed between typically developing teenagers and teenagers with dyslexia across chronological age-matched comparisons and a reading level-matched comparison, strongly suggesting atypically developed cognitive processing in the latter group. There was, however, no evidence to suggest differential phonological processing during silent reading in dyslexia, contrary to prior research suggesting that phonological processing deficits are a key causal factor in the reading difficulties associated with dyslexia. It may be the case that this sample of readers with dyslexia has had sufficient experience with print to develop more sophisticated phonological recoding abilities, and that whilst differences in phonological processing persist on certain tasks, their phonological recoding during reading did not differ significantly to typically developing readers. There was, however, some evidence to suggest that teenagers with dyslexia process orthography differently during silent reading. It may be the case that, whilst phonological recoding does not differ between teenagers with and without dyslexia, the interplay between both phonological and orthographic processing is different in teenagers with dyslexia, with older readers with dyslexia more reliant on orthographic processing during silent reading. The focus in this study was upon foveal processing only, and Experiment Two will focus upon phonological and orthographic processing in the parafovea during reading.

Chapter Five: Experiment Two: Parafoveal pre-processing of phonology and orthography in dyslexia

5.1: Introduction

In Experiment One, there were no significant differences between teenage readers with and without dyslexia with regards to phonological processing during silent sentence reading. All four participant groups had similar reading times on pseudohomophones relative to reading times on spelling controls, demonstrating that readers with and without dyslexia foveally process the speech sounds of words during silent reading. A separate issue, however, concerns the extent to which these items are processed prior to direct fixation during reading. Previous studies have demonstrated that as children get older and continue to gain further reading experience, the perceptual span (the region around the point of fixation from which information can be processed) increases (Häikiö, Bertram, Hyönä, & Niemi, 2009; Rayner, 1986; Sperlich, Schad, & Laubrock, 2015), and that the perceptual span may be smaller in extent in readers with dyslexia (Rayner, Murphy, Henderson, & Pollatsek, 1989). These findings suggest that reading ability may determine the extent to which information can be processed in the parafovea during silent reading. Less, however, is known about how young readers, either with or without dyslexia, specifically process the phonological and orthographic characteristics of words and nonwords in the parafovea. Experiment One examined reading times on pseudohomophones and spelling controls when they were directly fixated during reading. In Experiment Two, the boundary paradigm (Rayner, 1975) was used to examine whether readers with dyslexia parafoveally pre-process phonology and orthography during silent reading.

During silent reading, information from the upcoming word in the sentence is pre-processed parafoveally, prior to direct fixation. The parafovea comprises the region of the retina surrounding the fovea (roughly 2^o to 5^o around the point of fixation). Parafoveal pre-processing is an important component of skilled adult reading as it aids lexical identification of a word upon its subsequent fixation (see Drieghe, 2011, & Schotter, 2015 for reviews), and reading is disrupted if parafoveal pre-processing is prevented. In some cases, such as with short or frequent words, or words that are predictable from the prior sentence context, the upcoming word can be processed in the parafovea to the extent that a direct fixation is not required to identify it- the word is thus skipped (see Rayner, 1998). As discussed in Chapter Two, two paradigms have been particularly important in investigating parafoveal pre-processing.

Firstly, the moving window paradigm (McConkie & Rayner, 1975) has been used to investigate the perceptual span (the region from which useful information is acquired during reading). In this paradigm, a predetermined number of characters to the left and to the right of fixation are visible to the reader (characters outside of the window are masked or degraded), and the window moves with the reader's eyes, with its size remaining constant. This paradigm has been informative with regards to the spatial extent of parafoveal processing, but does not help to identify the specific features of the parafoveal word that are typically processed during reading. Secondly, and more importantly for this chapter, the boundary paradigm (Rayner, 1975) allows the experimenter to manipulate the preview that a reader receives of an upcoming word. An invisible boundary is inserted to the left of a target word in a sentence. When a saccade crosses the boundary, the preview is replaced with the target word. This change is typically not detected due to saccadic suppression, the retinal blur associated with an eye movement (Matin, 1974). The experimenter can, thus, vary the relationship between the preview and the directly fixated target word to investigate more precisely the type of information that is processed by readers parafoveally.

Researchers have investigated the extent to which readers pre-process phonological information during reading by observing the benefit to a reader in terms of fixation time on the target word associated with receiving a phonologically congruent preview relative to a phonologically incongruent preview. This technique was used by Pollatsek, Lesch, Morris, and Rayner (1992), who manipulated the parafoveal preview of a target word, using correct previews (e.g., *beach* previewed *beach*), homophones (*beech* previewed *beach*), and orthographic controls (*bench* previewed *beach*). If a word's phonological information is processed prior to its fixation, eventual fixations on the target word should be shorter following homophone previews compared to orthographic control previews, due to the shared phonology between the homophone preview and the target. Pollatsek et al. (1992) indeed found that a homophonic preview led to a greater preview benefit (i.e., the target word *beach* was fixated for a shorter period of time in instances when it was previewed by *beech* compared to *bench*). These results strongly suggest not only that phonological information is processed prior to a word receiving a direct fixation during reading, but that the processing of phonological information occurs pre-lexically, and may influence lexical identification itself.

It may be the case, however, that the extent to which an individual is able to parafoveally pre-process phonology is contingent upon their reading ability. There has been evidence to suggest that young readers have a smaller perceptual span than skilled adult readers (Rayner, 1986), and it may be that there is a greater allocation of processing resources on the fixated word in developing readers due to the increased processing difficulty, reducing the extent to which younger readers are able to parafoveally pre-process upcoming words. To investigate the influence of reading ability on parafoveal pre-processing of phonology, Chace, Rayner, and Well (2005) used an identical procedure to Pollatsek et al. (1992), but assigned adult participants, who had no diagnosed reading impairments, a percentile rank score for reading ability based on a short reading test, splitting them into more and less skilled reader groups. It was found that the less skilled reader group obtained no preview benefit for homophonic words over nonhomophonic words, and Chace et al. (2005) suggested that this is due to a greater allocation of processing resources on the currently fixated word in less skilled readers. It has also been demonstrated that less skilled readers are less likely to notice a homophone error in a proofreading task, and slower readers have a smaller perceptual span than faster readers (Jared, Levy, & Rayner, 1999; Rayner, Slattery, & Bélanger, 2010). Such research strongly suggests that the role of phonological processing, both foveally and parafoveally during reading, may be dependent on reading skill. Less skilled readers appeared to obtain a reduced preview benefit when compared to more skilled readers; it remains unclear, however, how readers with dyslexia process phonology in the parafovea.

As discussed at length in the previous chapters, it has been demonstrated that children with dyslexia have linguistic processing deficits and, as such, these deficits may affect their ability to pre-process upcoming words during reading. Relatively little, however, is known about how parafoveal processing takes place during silent reading in young readers with dyslexia. In addition to linguistic processing deficits, there is substantial evidence to suggest the link between phonological processing deficits and the reading difficulties associated with dyslexia (see Snowling, 2000). It may be the case that, in addition to linguistic processing deficits that hinder the ability to parafoveally pre-process the characteristics of the upcoming word in dyslexia, that these readers are also especially insensitive to phonological information in the parafovea. No studies to date, however, have directly investigated the parafoveal pre-processing of phonology during silent reading in dyslexia.

Participant groups for Experiment Two were constructed in an identical way to those used in Experiment One. Two typically developing groups of older and younger teenagers and two groups of readers with dyslexia, both younger and older, were recruited. Once again, this allowed the use of two chronological age-matched comparisons of readers with and without dyslexia, and one reading ability-matched comparison (Backman, Mamen, & Ferguson, 1984, though see Bryant & Goswami, 1986). It additionally allowed the investigation of differences in parafoveal pre-processing that are associated with chronological age- younger and older groups of participants were compared directly. The use of these types of comparison facilitates the investigation of atypical versus delayed development in dyslexia with regard to parafoveal processing, and the development of this ability in both typically developing readers and those with dyslexia.

In this experiment, participants silently read sentences containing the same correct target words as Experiment One. The boundary paradigm was used to manipulate the parafoveal preview that participants received; correct target words, pseduohomophones, and spelling controls were used as previews. No studies to date have investigated parafoveal processing of phonology in dyslexia during silent sentence reading, but four alternative patterns of data seem possible. Firstly, it may be the case that readers with dyslexia do not parafoveally pre-process the characteristics of the upcoming word during silent reading either at all, or to a very limited extent. If this were the case, readers with dyslexia would demonstrate equivalent reading times on the target word regardless of the type of preview received. This is a fairly unlikely pattern of data; it may be the case that very young readers do not parafoveally pre-processing upcoming words during reading, but the teenage participants in the present study were relatively experienced with print and had a number of years in formal education learning to read. Moreover, previous studies have demonstrated that parafoveal pre-processing during reading occurs in readers as young as eight years (Pagán, Blythe, & Liversedge, 2015) and, even given their reading difficulties, the participant with dyslexia should be at a reading level at which parafoveal pre-processing occurs to at least some extent. Secondly, readers with dyslexia may pre-process the orthographic characteristics of the upcoming word but not the phonological characteristics, due to the phonological processing deficits typically associated with dyslexia. If this were the case, readers with dyslexia would demonstrate shorter reading times on target words previewed by orthographically similar items than those previewed by orthographically dissimilar items, but no preview benefit would be observed on items previewed by pseudohomophones compared to spelling controls. Thirdly, readers with dyslexia may demonstrate pre-processing of both phonology and orthography during silent reading, and thus the preview benefit would be greatest for orthographically similar pseudohomophones and least for orthographically dissimilar spelling controls. Finally, a pattern in between the previously described possibilities may be observed whereby processing of orthography and phonology are not entirely independent. Participants with dyslexia may, for instance, demonstrate a pseudohomophone preview benefit, but only when pseudohomophones are orthographically similar to the correct target word (e.g., Pollatsek et al., 1992). Given these different possibilities, a number of specific hypotheses were made regarding global and local eye movement behaviour.

Firstly, consistent with prior research and the findings of Experiment One, a number of global eye movement differences were predicted between groups of readers with and without dyslexia. Children with dyslexia typically make longer and more fixations, shorter saccades, more regressions, and longer sentence reading times than their typically developing peers at an equivalent chronological age, and it was predicted that a similar pattern of global eye movement differences would emerge across both of the two chronological age-matched comparisons. Experiment One also demonstrated that teenagers with dyslexia made more fixations per sentence and had longer total sentence reading times than typically developing teenagers at an equivalent reading level. It was, therefore, predicted that global eye movement differences would also emerge between participant groups with and without dyslexia at an equivalent reading level in this experiment. Secondly, age-related differences in global eye movement behaviour were predicted between participant groups based on chronological age. Consistent with Experiment One, it was predicted that the two groups of older participants would demonstrate shorter fixations, fewer fixations and regressions per sentence, longer saccades, and shorter total sentence reading times than each of the two younger participant groups.

Hypotheses relating to the target word manipulations were also made. Firstly, it was predicted that for all four participant groups, reading times would be shortest on target words in trials where participants received an identical preview. In such trials, parafoveal pre-processing will be consistent with foveal processing, and as such this should facilitate faster lexical identification of the target word than in trials where the preview differs to the target word. Secondly, it was predicted that reading times would be shorter on target words (e.g., *cheese*) that were previewed by an orthographically similar item (e.g., *cheeze*/*cheene*) than reading times on target words (e.g., *crane*) that were previewed by orthographically dissimilar items (e.g., *krain*/*drauv*). It was predicted that the greater degree of orthographic overlap between items in orthographically similar conditions would facilitate parafoveal orthographic processing and be reflected in shorter fixation times on the target word. This is in line with prior research suggesting that readers as young as eight years parafoveally pre-process the orthographic characteristics of upcoming words during silent reading (Pagán, Blythe, & Liversedge, 2015, Tiffin-Richards & Schroeder, 2015). Even given the reading difficulties associated with dyslexia, the youngest readers with dyslexia in this sample should still be at a reading level at which parafoveal pre-processing on orthography may occur. Given the evidence to suggest that poor readers are less able to parafoveally pre-process the characteristics of the upcoming word in a sentence during reading, however, it was predicted that this effect may be reduced in readers with dyslexia.

Thirdly, an effect of phonological condition was predicted, such that reading times on target words would be shorter when previewed by a pseudohomophone than a spelling control word. Due to the shared phonological overlap between correct target words and their pseudohomophones, parafoveal pre-processing of the phonological characteristics of the pseudohomophone should facilitate lexical identification. Due to the lack of orthographic or phonological overlap between the correct target word and the equivalent spelling control, any pre-processing of this type of preview will not be beneficial to reading times on the target word. It was therefore predicted that a significant advantage would be observed in terms of reading times on items that were previewed by pseudohomophones compared to spelling controls. Due to both the phonological processing deficits associated with dyslexia, and the reduced capacity for parafoveal pre-processing, it was again predicted that a smaller pseudohomophone benefit would be observed in readers with dyslexia.

Fourthly, age-related differences in eye movement behaviour on the target word were predicted. The matching of participant groups allowed additional comparisons to be made between the typically developing groups, and between the two groups with dyslexia, to investigate age-related differences in parafoveal pre-processing during reading. Given the prior finding that the extent to which readers parafoveally pre-process words during reading is dependent upon reading ability, it was predicted that the overall preview benefit (the benefit in reading time on the target word observed when previewed by itself compared to a nonword item) would be greater in the older typically developing group than the younger typically developing group. It was also predicted that typically developing readers in both participant groups would demonstrate a significant preview benefit for target words previewed by pseudohomophones compared to spelling controls, although this effect was predicted to be smaller in the younger typically developing group. A similar pattern was predicted in the groups with dyslexia; a greater overall preview benefit in the older group with dyslexia compared to the younger, and a greater degree of parafoveal pre-processing of phonology in the older group. Note, however, that the extent to which parafoveal pre-processing of phonology takes place during reading in dyslexia was predicted to be reduced in both groups with dyslexia relative to the typically developing groups.

5.2: Method

Participants. As in Experiment One, there were four participant groups: Older typically developing teenagers (TDO); older teenagers with dyslexia (DO); younger typically developing teenagers (TDY); and younger teenagers with dyslexia (DY). Participant groups were matched to allow older (TDO-DO) and younger (TDY-DY) chronological age-matched comparisons, and a reading level-matched comparison (DO-TDY). All participants had English as their first language, and all had normal or corrected-to-normal vision. Participants in the two groups with dyslexia had received an independent diagnosis of dyslexia, and all typically developing participants had no known reading difficulties at the time of testing. To ensure that participants with dyslexia were indeed impaired in their reading compared to the typically developing participants, participants were also tested on their reading ability. This also allowed the matching of participants with and without dyslexia based on their reading ability.

In addition to reading ability, participants were also tested on their nonverbal IQ. This data was used to ensure that reading difficulties observed in the groups with dyslexia were not confounded with differences in general intelligence. Participants were further tested on their vocabulary as an additional measure of reading difficulties, and their phonological processing ability, as an additional measure of how readers process phonology independent of the sentence reading task. Means and standard deviations from each of the pen and paper assessment measures can be seen in Table 5.1.

Table 5.1. Participant group means and standard deviations and pen and paper results.

	TDO	DO	TDY	DY
N	30	21	21	14
Age, in months	207 (5)	206 (11)	177 (4)	173 (10)
Age range	192 – 216	185 - 245	170 – 185	155 -183
Word reading, SS[a]	108 (6.09)	95 (7.78)	102 (9.52)	85 (15.3)
Word reading. raw[a]	125 (3.22)	118 (4.22)	119 (5.5)	108 (8.96)
Pseudoword decoding[a]	102 (7.4)	88 (12.13)	98 (9.1)	83 (9.54)
IQ[b]	90 (14.73)	93 (9.13)	94 (16.7)	91 (14.78)
Vocabulary[c]	104 (7.07)	101 (9.55)	100 (7.87)	97 (12.12)
Phonological processing[d]	95 (12.44)	90 (9.61)	96 (11.95)	90 (17.16)

Note. Standard deviations in parentheses. [a]WIAT-II subtests, standardised scores; [b]RPM standardised scores; [c]BPVS standardised scores; [d]CTOPP sum of subtest standardised scores. TDO = older typically developing group, DO = older group with dyslexia, TDY = younger typically developing group, DY = younger group with dyslexia.

Materials. Pen and paper assessments were those used in Experiment One.

Group matching procedure. Recall that four specific participant group comparisons were outlined in Chapter Four. Comparison One was between older teenagers with and without dyslexia. The two participant groups for this comparison were matched on chronological age ($t(49) = 0.55$, $p = .58$). A total of 33 older typically developing participants were tested, with 30 forming the eventual group matched to the older group with dyslexia on chronological age. These two groups were also required to be significantly different with regards to their reading ability. Using the standardised scores from the WIAT-II subtest, it was ensured that significant differences were present between groups, such that the typically developing group were significantly better readers than the group with dyslexia ($t(49) = 6.71$, $p < .001$). There was also a significant difference between the two groups in pseudoword decoding ($t(49) = 5.37$, $p < .001$), but no significant differences in IQ, vocabulary, or phonological processing (all $ts(49) < 2$, all ps $> .14$).

Comparison Two was between the older group with dyslexia and the younger typically developing group, who were matched on reading level, as measured by raw scores on the word reading subtest of the WIAT-II ($t(40) = 1.51$, $p = .2$). Significant differences in chronological age, however, were observed ($t(40) = 11.03$, $p < .001$). In addition to these, significant differences were observed between groups in pseudoword decoding ($t(40) = 3.4$, $p < .01$). No significant differences were observed in phonological processing, IQ, or vocabulary (all $ts(40) < 2$, all ps $> .13$). These two groups were, thus, matched on reading ability, but mismatched on chronological age.

Comparison Three was between the younger typically developing group and the younger group with dyslexia, serving as a second chronological age-matched comparison. These two groups were, thus, matched on chronological age ($t(33) = 1.54$, $p = .21$), but significantly differed in their standardised scores on the word reading subtest ($t(33) = 4.08$, $p < .001$). In addition to this, there were significant differences in pseudoword decoding ($t(33) = 5.04$, $p < .001$), but no significant differences in IQ, vocabulary, or phonological processing (all $ts(33) < 1.6$, all ps $> .26$).

Finally, Comparison Four was between the older and younger typically developing groups, and the older and younger groups with dyslexia. The structure of the group matching procedures reported thus far allowed for age-related differences between groups to be investigated in both typically developing readers and readers with dyslexia. There were significant differences between the older and younger participant groups in chronological age, both typically developing and with dyslexia (all $ts(49) >$

8.79, all *ps* <.001), and significant differences between each in word reading and vocabulary (all *ts*(49) >1.96, all *ps* <.05). There were no differences in nonverbal IQ (all *ts*(49) < 1, all *ps* >.33)

Apparatus. An EyeLink 2K eye tracker (SR Research, Toronto, Canada) was used to record eye movements during reading from the right eye, although viewing was binocular. As in Experiment One, sentences were presented on a 19” Viewsonic CRT monitor operating at 100Hz at a viewing distance of 60cm. All sentences were presented in black, Courier New font size 14, on a grey background. A chinrest and forehead rest were used to minimise head movements, and a Microsoft gamepad was used to answer comprehension questions and to indicate that the participant had finished reading each sentence.

Stimuli and design. The twenty four triplets used in Experiment Two were identical to those used in Experiment One, with each triplet comprised of a correct target word, a pseudohomophone, and a spelling control nonword. As described in Chapter Three, pre-screening procedures were carried out to allow the selection of two sentences for each target triplet. The second of the two sentences selected were used in Experiment Two. Participants, thus, read 24 novel experimental sentences in a randomised order, with preview type rotated across three counterbalanced files. Eight sentences contained target words previewed by themselves, eight sentences contained target words previewed by pseudohomophones, and eight sentences contained target words previewed by spelling controls. Comprehension questions followed 25% of experimental trials.

Procedure. The experimental procedure used in Experiment Two was identical to Experiment One. Following the experiment, participants were asked if they had noticed ‘anything strange’ whilst reading the sentences. If participants indicated that they had noticed the boundary change occur, they were asked to estimate on how many trials they observed the change. If they indicated that they had noticed a change on five or more trials, their results were excluded from the analyses. A total of 16 participants indicated that they had noticed something strange whilst reading the sentences. 15 participants specifically noticed one or more boundary changes, with 4 indicating that they had been aware of the change on five or more trials, and their results were excluded from the experiment.

5.3: Results

Global eye movement results will be reported from all trials, whereas local eye movement results will be reported for a subset of experimental sentences only in which it could be ensured that the boundary change occurred at the correct moment. Eye movement data was firstly cleaned using the clean function in EyeLink DataViewer (SR Research, Ontario, Canada) in a method identical to that in Experiment One.

Use of the boundary paradigm involves the preview changing at the moment a saccade crosses the invisible boundary prior to the target word. However, due to display limitations or tracking difficulties, which are a particular problem when testing younger participants, the boundary change is often implemented slightly too early, or slightly too late. In such instances it is difficult to ascertain whether parafoveal pre-processing of the upcoming word has taken place as intended, and these trials were removed from final analyses. In the case that the boundary change occurs too early, prior to a saccade crossing the boundary, it may be the case that participants do not pre-process the preview at all, and any preview benefit observed is solely the result of pre-processing the target word itself rather than the preview. It is, thus, vital to exclude such instances from the results. Similarly, boundary changes that occur too late allow participants to fixate the preview, which should never occur, and may allow participants to observe the change to the target word. Removing both early and late boundary changes from the data leaves trials in which the boundary change occurred at the correct time, and it can be ensured that parafoveal pre-processing of the preview took place.

Trials in which the display change occurred early, prior to the saccade crossing the boundary, were identified by determining instances in which the display change occurred during a fixation on a word prior to the boundary. These trials were subsequently removed from local analyses, and accounted for 6% of the total experimental trials. It is also important to remove trials in which the intended saccadic target was the pre-target word, but in which the display change was triggered due to the retinal jutter associated with high velocity eye movements. Such trials are not removed in the procedure for identifying early display change trials as described above as these changes do not occur during a fixation, but rather during a saccade. The removal of these trials accounted for 1% of all experimental trials. Trials in which the display change occurred late, or after a saccade had crossed the boundary, were calculated against a leniency criteria. Due to the difficulty in ascertaining precisely when a computer monitor has refreshed on a millisecond by millisecond basis, a leniency criteria for late boundary changes is adopted- a common criterion in the field is 10ms (Slattery, Angele, & Rayner, 2011). This meant that all trials in which the boundary change did not occur in the first 10ms of the boundary being crossed were identified and removed. With this leniency criteria, 11% of trials were identified to include late boundary changes and excluded from local analyses. Finally, it was important to remove trials in which the pretarget word in the sentence was skipped during first pass reading. In these instances, pre-processing on the target word may not have occurred, and the removal of these trials accounted for 22% of all trials. Following these procedures, 1269 trials remained out of an initial 2064 trials. Through these cleaning procedures, it was ensured that trials in which the display change did not occur at the correct moment were not included in the final analyses, allowing a tightly controlled investigation of parafoveal pre-processing of phonology and orthography.

As in Experiment One, a number of global and local eye movement measures were analysed using linear mixed effects models (LME models) within the R environment for statistical computing (Bates, Maechler, Bolker, & Walker, 2014). Participants and preview type were included as random factors, with the full random structure as default. The sdif function was used to compare conditions successively, rather than iteratively to an intercept term, allowing the three typically developing versus dyslexia participant group comparisons outlined above to be made within each model. These comparisons are labelled main model in Table 5.6. Planned contrasts were additionally used to compare the older and younger typically developing groups and the older and younger groups with dyslexia, as this comparison was also of theoretical interest. These comparisons are designated as age-related contrasts in Table 5.6. Contrast matrices designated the conditions to be directly compared, and an additional LME model was run for each of these comparisons, syntactically identical to the main LME models. Additionally, in the event of significant interactions, further contrasts were run to examine the relevant conditions for each interaction. In the instances where models failed to converge, the random structure of each model was pruned until convergence was achieved. Regression coefficients (b), standard errors (SE) and t values (z values where appropriate) are reported, and, as is custom, 1.96 was taken as the significance level for both t and z values.

Table 5.2. Means and standard deviations for global eye movement measures.

	TRT	Fix Count	MFD	Skip	Reg Count
TD Older	4962	14.95	231	0.4	4.01
	(1067)	(3.61)	(108)		(2.65)
D Older	6832	19.93	253	0.32	4.86
	(2352)	(6.15)	(123)		(2.61)
TD Younger	5773	16.51	255	0.39	4.11
	(1844)	(4.71)	(124)		(2.73)
D Younger	8729	24.77	281	0.25	5.11
	(3435)	(8.73)	(150)		(3.7)

Note. Standard deviations in parentheses. TRT = total reading time, in milliseconds; Fix Count = fixation count, in mean number of fixations per sentence; MFD = mean fixation duration, in milliseconds; Skip = probability of words being skipped during first pass reading; Reg Count = regression count, in mean number of regressions per sentences.

Global eye movement results. Means and standard deviations for global measures can be seen in Table 5.2, and fixed effects estimates in Table 5.3. LME models were run on global eye movement measures, with the syntax for each model being (dependent variable ~ group + (1|participant) + (1+group|triplet number), with the sdif function used to compare conditions successively (i.e., TDO with DO, DO with TDY, and TDY with DY). In addition to these comparisons, additional contrasts were run to investigate participant group differences between the TDO and TDY groups and between the DO and DY groups. The results of these contrasts are reported below those from the main LME model. The measures analysed were those used in Experiment One: total sentence reading time, mean number of fixations per sentence, mean number of regressions per sentences, word skipping probability, and mean fixation duration.

Differences in global eye movement behaviour were predicted between readers with and without dyslexia, due to the linguistic processing deficits associated with dyslexia. These were investigated using four different sets of comparisons. The first comparison was between older teenagers with and without dyslexia who were matched on chronological age. The older teenagers with dyslexia had longer sentence reading times, made more fixations per sentence, were less likely to skip a word during reading, and had significantly longer mean fixation durations than their typically developing counterparts (see Table 5.3). An identical pattern was observed in the third comparison, the younger chronological age-matched comparison. This pattern of results strongly suggests that participants with dyslexia had more difficulty cognitively processing the sentences during reading than their typically developing peers. To ensure that the basis of these differences was not the lower reading ability in the readers with dyslexia, a reading level-matched comparison was also used. A number of global eye movement differences also emerged in this comparison; longer total sentence reading times, more fixations per sentence, and a lesser likelihood of word skipping in the group with dyslexia relative to the typically developing group matched on reading level. Consistent with the findings of Experiment One, this suggests atypical rather than delayed development in the readers with dyslexia. Across the two age-related comparisons, it was firstly observed that older readers had significantly shorter mean fixation durations than younger readers, and made fewer fixations per sentence, both for the typically developing and dyslexia comparisons. It was secondly observed that younger readers with dyslexia were significantly less likely to skip a word during reading than older readers with dyslexia, whereas this difference was not observed between the typically developing groups.

In summary, a robust pattern of differences has been observed between readers with and without dyslexia in terms of their global eye movement behaviour. Readers with dyslexia had longer total sentence reading times, made more fixations, and were less likely to skip a word than their typically developing peers. This pattern was observed across two chronological age-matched comparisons and one reading level-matched comparison, strongly suggesting that these differences are not simply the result of delayed development in cognitive processing in dyslexia, but instead reflect atypical development.

Local eye movement analyses. Means for local measures of eye movement behaviour between groups can be seen in Table 5.4, with fixed effects estimates shown in Tables 5.5 and 5.6. As in Experiment One, local eye movement analyses were conducted to investigate reading times on the target word only. Correct target words (e.g., *summer*/*circle*) were previewed by five different types of stimuli; correctly spelled target words (e.g., *summer*/*circle*, with no boundary change), orthographically similar pseudohomophones (e.g., *summur*), orthographically similar spelling controls (e.g., *summor*), orthographically dissimilar pseudohomophones (e.g., *sercle*), or orthographically dissimilar spelling controls (e.g., *norcle*). The influence of phonological condition and orthographic similarity in terms of their preview benefit were therefore investigated. The first analysis (Model 1) collapsed correct target word preview conditions across orthographic similarity, and compared them to each type of nonword preview, as in Experiment One. Recall that this was done as there was no meaningful comparison to be made between orthographic similarity conditions concerning the correct target word. The second (Model 2) excluded the correctly spelled previews, and compared reading times on correct target words following each type of nonwords preview only.

Model 1. In this analysis, reading times on correct target words on trials in which there was no boundary change were compared to reading times in trials where the correct target word was previewed by: 1) Orthographically similar pseudohomophones; 2) Orthographically similar spelling controls; 3) Orthographically dissimilar pseudohomophones; 4) Orthographically dissimilar spelling controls. An LME model with group and preview type as the two sole fixed factors was constructed for each dependent measure, with an interaction between the two and participants and target word/nonword triplet number as random factors with the full random structure. The syntax for the models was (dependent variable ~ group*preview type + (1+preview type|participant) + (1+group*preview type|triplet number). All terms in the model were compared iteratively to the intercept term.

LME models were constructed for single and first fixation duration, gaze duration, and total reading time. Firstly, a main effect of preview type was consistently observed across measures (Terms 2, 3, and 4 in Table 5.5) for three of the four non-identical preview types. Reading times were longer for target words previewed by orthographically similar and dissimilar spelling controls, and orthographically dissimilar pseudohomophones, across all four measures relative to reading times on target words previewed by themselves. Concerning reading times on target words previewed by orthographically similar pseudohomophones, however, there were no significant differences in reading times in any local measure (Term 1 in Table 5.5). Finally, there were no interactions between preview type and group in any local measure (Terms 8-19 in Table 5.5).

Secondly, participant group differences emerged. The older group with dyslexia had significantly longer single fixation durations and total reading times than the older typically developing group. (Term 5 in Table 5.5). The younger group with dyslexia had longer reading times on all local measures than the older typically developing group (Term 3 in Table 5.5). No significant differences were observed between the older and younger typically developing groups.

In summary, Model 1 analyses demonstrated that there was no significant cost in terms of reading times when reading a target word previewed by an orthographically similar pseudohomophone compared to receiving a correct preview in any local eye movement measure. In contrast, a significant cost was observed when the target word was previewed by each of the three alternative preview types. Group differences in reading times were also observed between the older typically developing group and the younger group with dyslexia.

Table 5.3. Fixed effects estimates for global eye movement measures

	TRT			Fix Count			MFD		
	b	SE	t	b	SE	t	b	SE	t
Intercept (grand mean)	8.72	0.03	307.97	19.04	0.54	34.97	5.45	0.01	433.70
Group (TDO vs. DO)	0.29	0.06	4.79	4.98	1.11	4.50	0.08	0.03	2.40
Group (DO vs. TDY)	-0.16	0.07	-2.44	-3.42	1.20	2.85	0.01	0.03	0.40
Group (TDY vs. DY)	0.39	0.07	5.23	8.26	1.34	6.16	0.07	0.04	1.70
Age-related contrasts									
Group (TDO vs. TDY)	0.11	0.08	1.34	4.98	1.11	4.50	0.09	0.03	2.80
Group (DO vs. DY)	0.05	0.12	0.31	8.26	1.34	6.16	0.08	0.04	2.10

	Skip				Reg Count		
	b	SE	z	p	B	SE	t
Intercept (grand mean)	0.72	0.06	11.41	<.001	4.76	0.21	19.23
Group (TDO vs. DO)	0.37	0.10	3.67	<.001	0.78	0.41	1.61
Group (DO vs. TDY)	0.31	0.11	2.86	<.01	-0.76	0.53	1.51
Group (TDY vs. DY)	0.65	0.13	5.19	<.001	1.56	0.68	2.31
Age-related contrasts							
Group (TDO vs. TDY)	-0.06	0.10	-0.62	0.53	-0.03	0.43	0.11
Group (DO vs. DY)	-0.34	0.12	-2.71	0.01	-0.14	0.61	0.21

Note. TDO = Older typically developing group; DO = Older group with dyslexia; TDY = younger typically developing group; DY = younger group with dyslexia t or z values above 1.96 indicate statistically significant difference. SE = standard error. TRT = total reading time, Fix Count = fixations per sentence, MFD = mean fixation duration, Skip = likelihood of skipping a word, Reg Count = number of regressions per sentence.

Table 5.4. Means and standard deviations for local eye movement measures

		TDO		DO		TDY		DY	
		Orth. similar	Orth. dissimilar	Orth. Similar	Orth. Dissimilar	Orth. similar	Orth. dissimilar	Orth. similar	Orth. dissimilar
SFD	Correct targets	219 (101)	203 (67)	225 (85)	225 (77)	213 (52)	228 (66)	286 (113)	258 (105)
	Pseudohomophones	223 (62)	261 (87)	262 (84)	284 (97)	238 (73)	270 (84)	305 (168)	360 (99)
	Spelling Controls	243 (69)	253 (71)	253 (102)	335 (165)	252 (72)	288 (87)	317 (106)	393 (214)
FFD	Correct targets	217 (98)	202 (65)	225 (85)	227 (88)	214 (51)	235 (76)	282 (109)	262 (99)
	Pseudohomophones	214 (63)	253 (85)	263 (103)	265 (96)	237 (72)	265 (82)	276 (140)	331 (107)
	Spelling Controls	235 (71)	245 (71)	245 (95)	312 (159)	252 (71)	268 (85)	307 (101)	358 (206)
GD	Correct targets	230 (102)	223 (88)	241 (120)	266 (134)	224 (69)	249 (98)	344 (153)	318 (175)
	Pseudohomophones	234 (66)	273 (90)	288 (127)	311 (105)	240 (72)	284 (92)	367 (166)	448 (323)
	Spelling Controls	267 (119)	267 (89)	279 (111)	361 (179)	259 (81)	345 (184)	402 (210)	416 (202)
TT	Correct targets	319 (221)	279 (203)	387 (265)	426 (269)	280 (140)	338 (214)	545 (333)	392 (235)
	Pseudohomophones	291 (140)	346 (229)	426 (290)	444 (322)	349 (215)	335 (126)	495 (298)	542 (395)
	Spelling Controls	320 (194)	315 (221)	379 (209)	442 (271)	354 (191)	462 (362)	544 (333)	551 (406)

Note. Standard deviations in parentheses. TDO = Older typically developing group; DO = Older group with dyslexia; TDY = younger typically developing group; DY = younger group with dyslexia. SFD = single fixation duration, in milliseconds; FFD = first fixation duration, in milliseconds; GD = gaze duration, in milliseconds, TT = total fixation time, in milliseconds

Model 2. For these analyses, all trials in which the target word was previewed by itself were excluded. Phonological condition (pseudohomophone previews versus spelling control previews) and orthographic similarity (orthographically similar versus dissimilar previews) were orthogonally manipulated, and reading times were analysed for each of the four participant groups. As in Experiment One, these three factors were entered as interacting fixed factors in an LME model, with participant and triplet number as random factors (dependent variable ~ phoncond*orthcond*group + (1+phoncond*orthcond|participant) + (1+phoncond*group|triplet number). The full random structure was used where possible, but random factors were trimmed if convergence did not occur. The sdif function was used to compare terms in the model successively, and, as outlined in the global eye movement results, additional contrasts were run to compare the TDO group with the TDY group, and the DO group with the DY group. Results from these contrasts are reported below the main model in Table 5.6. For each fixed factor, a number of hypotheses were made, and each will be evaluated in turn.

Participant group. Longer reading times were predicted in the groups with dyslexia compared to the typically developing groups, due to the cognitive processing deficits associated with dyslexia. Across each of the two chronological age-matched comparisons, longer reading times were observed in all four local measures for the groups with dyslexia compared to the typically developing groups (Terms 1 and 3 in Table 5.6). No significant participant group differences were observed in any local measure in the reading level-matched comparison (Term 2 in Table 5.6). These results are consistent with those observed in Experiment One. It was also predicted that longer reading times would be observed in older groups compared to younger groups of readers. This effect was observed only in total fixation time for the typically developing groups (Term 16 in Table 5.6), but was consistently observed across local measures in the two groups with dyslexia (Term 17 in Table 5.6).

Orthographic similarity. The extent to which a parafoveal preview overlaps orthographically with a target word is an important factor in fixation time on the latter, as a greater degree of overlap facilitates lexical identification. It was, therefore, predicted that target words previewed by items in orthographically similar conditions would be fixated for a shorter period than those in orthographically dissimilar conditions. In single and first fixation duration, and gaze duration, a main effect of orthographic similarity was found, indicating significantly shorter reading times on target words previewed by orthographically similar nonwords than orthographically dissimilar nonwords (Term 5 in Table 5.6).

It was also predicted that this effect would be more robust in the typically developing groups, as there is evidence to suggest that readers with dyslexia are less able to parafoveally pre-process words during reading. In fact, no interactions were observed between participant group and orthographic similarity, suggesting that reading times on target words that were previewed by items in orthographically similar conditions were shorter across all participant groups (Terms 9, 10 and 11 in Table 5.6). This pattern of results strongly suggests that all participants were similarly able to parafoveally pre-process the orthographic characteristics of the parafoveal word during silent reading.

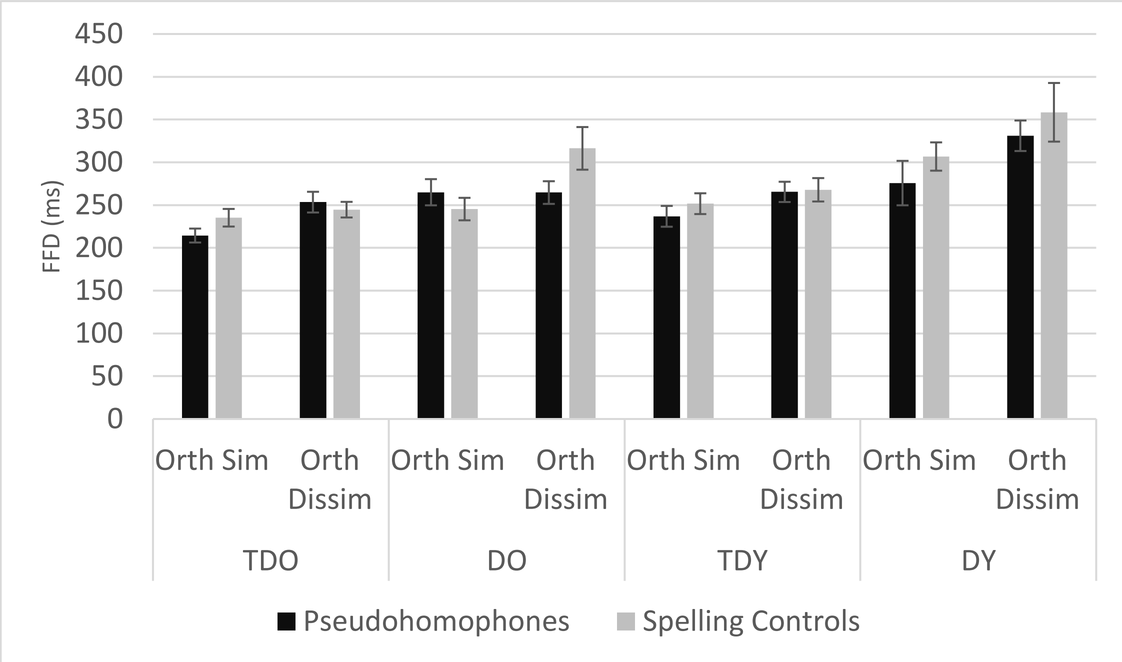
In summary, longer reading times were observed on items previewed by orthographically dissimilar items, regardless of participant group. All participants, both typically developing and with dyslexia, demonstrated a significant preview benefit for orthographically similar items compared to orthographically dissimilar items, suggesting that teenage readers with dyslexia parafoveally pre-process orthography during reading.

Phonological condition. Phonological condition was the final factor in the manipulation; in the trials that were included in the Model 2 analyses, participants received either a pseudohomophone or spelling control preview. If participants parafoveally pre-processed the phonological characteristics of words during reading, shorter reading times should be observed in trials with a pseudohomophone preview. This effect was observed in gaze duration, demonstrating a significant phonological preview benefit, and was marginal in single and first fixation duration (Term 4 in Table 5.6).

It was also predicted that participants with dyslexia would be less able to parafoveally pre-process phonology, and, thus, show a reduced benefit in terms of reading times when receiving a pseudohomophone preview compared to a spelling control preview. Following the findings from the manipulation of orthographic similarity, there were no group by phonological condition interactions, suggesting that all four participant groups were similarly able to pre-process the phonological characteristics of the parafoveal word (Terms 6, 7 and 8 in Table 5.6). Recall that a similar finding was obtained in Experiment One, where participants with dyslexia demonstrated a pseudohomophone advantage during silent reading; in Experiment Two, participants with dyslexia additionally demonstrated a phonological preview benefit.

Two three-way interactions were additionally observed, both concerning the older group with dyslexia in comparison to each of the two typically developing groups. Firstly, a three-way interaction was observed between participant group (TDO vs DO), phonological condition, and orthographic similarity in single and first fixation duration (Term 13 in Table 5.6). Contrasts were run to investigate reading times on target words following each type of preview, for each of the two participant groups in each of the two orthographic similarity conditions. A significant pseudohomophone preview benefit was observed only in the older group with dyslexia on orthographically dissimilar trials ($t = 2.45$) in single fixation duration. A 20ms trend towards a pseudohomophone preview benefit in the older typically developing group was observed in orthographically similar conditions only ($t = 1.69$). This pattern was not observed in the older typically developing group on orthographically dissimilar preview items, nor in the older group with dyslexia on orthographically similar preview items (both $ts < 1.1$). Contrasts in first fixation duration revealed a similar pattern, which can be observed below in Figure 5.1. Secondly, a marginal 3 way interaction was observed concerning the older group with dyslexia and the younger typically developing group in single and first fixation duration. Contrasts were again used to investigate these effects, and, consistent with the first 3 way interaction, a significant pseudohomophone preview benefit was observed only in the older group with dyslexia on orthographically dissimilar items. This was significant in single fixation duration ($t = 2.15$), and marginally significant in first fixation duration ($t = 1.81$).

Figure 5.1: Mean first fixation duration on target word by preview type, participant group, and orthographic similarity.



Finally, concerning the age-related participant group comparisons, all four participant groups demonstrated shorter reading times on target words previewed by pseudohomophones than spelling controls (Terms 18 and 19 in Table 5.6), and all four participant groups demonstrated shorter reading times on target words previewed by orthographically similar items (Term 20 and 21 in Table 5.6). A three-way interaction was observed between participant group (older and younger groups with dyslexia), phonological condition and orthographic similarity (Term 23 in Table 5.6). Contrasts were run to investigate reading times on items previewed by pseudohomophones compared to spelling controls for each of the two groups. As in the previous contrasts, the older group with dyslexia had shorter reading times on items previewed by orthographically dissimilar pseudohomophones than orthographically dissimilar spelling controls in first fixation duration (t = 2.06) and gaze duration (t = 2.06).

In summary, a significant phonological preview benefit was observed. In trials in which target words were previewed by pseduohomophones, reading times on the target word were shorter than when previewed by spelling controls. This demonstrates that participants parafoveally pre-processed the phonological characteristics of the upcoming word during silent reading, and that this facilitated lexical identification of the target word. The older group with dyslexia also demonstrated a greater cost in terms of reading times when reading orthographically dissimilar spelling controls relative to all other participant groups. Whilst it was predicted that readers with dyslexia would be less able to pre-process phonology during reading, this experiment found no evidence to suggest differential parafoveal processing of phonology; a significant effect of phonological condition was observed regardless of participant group.

Table 5.5. Fixed effects estimates for Model 1 analyses (reading times on target words across the different preview conditions).

Term No.		Single fixation duration			First fixation duration			Gaze duration			Total time		
		b	SE	t	b	SE	t	b	SE	t	b	SE	t
	Intercept (TDO, Correct)	5.25	0.05	112.24	5.26	0.04	124.20	5.31	0.05	98.78	5.47	0.07	78.86
1	Target (OS P)	0.09	0.05	1.73	0.05	0.05	0.86	0.10	0.06	1.72	0.09	0.08	1.15
2	Target (OD P)	0.24	0.06	3.95	0.21	0.06	3.32	0.22	0.06	3.39	0.19	0.08	2.47
3	Target (OS S)	0.18	0.06	2.94	0.14	0.06	2.23	0.21	0.07	3.18	0.15	0.08	1.9
4	Target (OD S)	0.25	0.05	4.81	0.20	0.05	3.73	0.24	0.06	4.24	0.20	0.07	2.62
5	Group (DO)	0.12	0.06	1.96	0.10	0.06	1.70	0.12	0.07	1.70	0.31	0.09	3.36
6	Group (TDY)	0.10	0.06	1.57	0.11	0.06	1.89	0.09	0.07	1.20	0.11	0.10	1.15
7	Group (DY)	0.32	0.07	4.60	0.28	0.06	4.46	0.39	0.08	4.89	0.51	0.10	4.85
8	Group x Target (DO, OS P)	0.05	0.08	0.63	0.09	0.08	1.19	0.05	0.08	0.68	-0.01	0.11	0.08
9	Group x Target (DO, OD P)	-0.03	0.09	0.38	-0.06	0.09	0.67	0.02	0.09	0.18	-0.08	0.11	0.71
10	Group x Target (DO, OS S)	-0.13	0.09	1.47	-0.07	0.08	0.89	-0.09	0.09	1.06	-0.13	0.11	1.17
11	Group x Target (DO, OD S)	0.11	0.08	1.43	0.07	0.08	0.89	0.11	0.08	1.32	-0.05	0.11	0.45
12	Group x Target (TDY, OS P)	-0.03	0.08	0.34	0.00	0.08	0.05	-0.06	0.09	0.71	0.03	0.11	0.28
13	Group x Target (TDY, OD P)	-0.01	0.09	0.14	-0.04	0.09	0.46	0.00	0.09	0.04	0.03	0.11	0.23
14	Group x Target (TDY, OS S)	-0.05	0.09	0.53	-0.03	0.09	0.28	-0.09	0.10	0.90	0.01	0.12	0.08
15	Group x Target (TDY, OD S)	0.04	0.08	0.46	-0.04	0.08	0.43	0.09	0.09	1.05	0.13	0.11	1.17
16	Group x Target (DY, OS P)	-0.02	0.10	0.21	-0.08	0.09	0.91	-0.03	0.09	0.27	-0.10	0.13	0.75
17	Group x Target (DY, OD P)	-0.02	0.10	0.18	-0.02	0.10	0.20	0.01	0.10	0.06	-0.07	0.12	0.57
18	Group x Target (DY, OS S)	-0.03	0.10	0.32	-0.02	0.09	0.21	-0.03	0.10	0.28	0.01	0.12	0.07
19	Group x Target (DY, OD S)	0.03	0.09	0.35	0.00	0.09	0.01	-0.04	0.09	0.49	-0.07	0.12	0.56

Note. TDO = Older typically developing group; DO = Older group with dyslexia; TDY = younger typically developing group; DY = younger group with dyslexia, OS = orthographically similar, OD = orthographically dissimilar. P = pseudohomophone, S = spelling control. t or z values above 1.96 indicate statistically significant difference. SE = standard error

Table 5.6. Fixed effects estimates for Model 2 (reading times on target words following misspelled preview items only

Term No		Single fixation duration			First fixation duration			Gaze duration			Total time		
		b	SE	t	b	SE	t	b	SE	t	b	SE	t
	Main model												
	Intercept (grand mean)	5.57	0.03	160.22	5.52	0.03	199.06	5.64	0.04	154.39	5.85	0.05	128.66
1	Group (TDO vs. DO)	0.12	0.05	2.27	0.10	0.05	2.00	0.13	0.06	2.20	0.24	0.08	3.06
2	Group (D vs. TDY)	-0.04	0.06	0.64	-0.01	0.05	0.27	-0.07	0.06	1.03	-0.09	0.08	1.04
3	Group (TDY vs. DY)	0.22	0.07	3.09	0.16	0.06	2.70	0.29	0.07	4.00	0.30	0.09	3.15
4	Phon	0.06	0.04	1.66	0.06	0.03	1.68	0.07	0.03	2.13	0.04	0.03	1.08
5	Orth	0.16	0.06	2.65	0.12	0.05	2.59	0.16	0.06	2.57	0.07	0.08	0.90
6	Group x Phon (TDO vs. DO)	-0.01	0.06	0.16	-0.02	0.06	0.28	-0.02	0.07	0.29	-0.05	0.09	0.59
7	Group x Phon (DO vs. TDY)	0.03	0.07	0.38	0.01	0.07	0.14	0.06	0.07	0.80	0.09	0.09	1.00
8	Group x Phon (TDY vs. DY)	-0.02	0.08	0.21	0.03	0.07	0.45	-0.08	0.08	1.01	-0.03	0.10	0.27
9	Group x Orth (TDO vs. DO)	0.06	0.06	0.95	-0.01	0.07	0.13	0.09	0.07	1.31	0.02	0.09	0.19
10	Group x Orth (DO vs. TDY)	-0.02	0.07	0.29	-0.02	0.07	0.27	0.03	0.07	0.44	0.04	0.09	0.47
11	Group x Orth (TDY vs. DY)	-0.02	0.10	0.18	0.04	0.08	0.58	-0.13	0.09	1.43	-0.11	0.11	0.98
12	Phon x Orth	0.01	0.07	0.21	-0.03	0.07	0.40	-0.03	0.06	0.47	-0.03	0.07	0.43
13	Group x Phon x Orth (TDO vs. DO)	0.30	0.12	2.56	0.30	0.12	2.46	0.23	0.12	1.90	0.13	0.17	0.79
14	Group x Phon x Orth (DO vs. TDY)	-0.26	0.13	2.03	-0.27	0.13	2.01	-0.11	0.13	0.86	-0.01	0.18	0.08
15	Group x Phon x Orth (TDY vs. DY)	0.01	0.15	0.05	-0.06	0.15	0.42	-0.17	0.14	1.21	-0.21	0.20	1.02
	Age-related contrasts												
16	Group (TDO vs. TDY)	0.09	0.06	1.56	0.09	0.05	1.61	0.07	0.06	1.12	0.16	0.08	2.01
17	Group (DO vs. DY)	0.19	0.07	2.59	0.15	0.06	2.51	0.23	0.07	3.27	0.21	0.09	2.31
18	Group x Phon (TDO vs. TDY)	0.01	0.06	0.14	-0.02	0.07	0.23	0.04	0.07	0.52	0.04	0.09	0.42
19	Group x Phon (DO vs. DY)	0.02	0.08	0.26	0.05	0.07	0.73	-0.02	0.07	0.23	0.07	0.10	0.74
20	Group x Orth (TDO vs. TDY)	0.04	0.07	0.58	-0.03	0.07	0.41	0.11	0.07	1.64	0.06	0.09	0.67
21	Group x Orth (DO vs. DY)	-0.04	0.10	0.38	0.04	0.07	0.48	-0.09	0.07	1.3	-0.05	0.10	0.52
22	Group x Phon x Orth (TDO vs. TDY)	0.06	0.13	0.46	0.04	0.13	0.29	0.11	0.13	0.82	0.10	0.18	0.56
23	Group x Phon x Orth (DO vs. DY)	-0.27	0.15	1.76	-0.33	0.14	2.34	-0.27	0.14	1.93	-0.20	0.20	1.04

5.4: Discussion

Summary. In Experiment Two, the aim was to investigate parafoveal pre-processing of phonology and orthography during silent reading in teenagers with and without dyslexia. The results of this study thus extend the findings of Experiment One, where the focus was on foveal processing of phonology and orthography, to parafoveal pre-processing. Together, these results provide a comprehensive investigation of phonological processing during silent reading, in both typically developing readers and readers with dyslexia.

In terms of global eye movement behaviour, a number of differences were observed between readers with and without dyslexia that were consistent with both the findings of Experiment One, and the experimental literature concerning eye movements during reading in dyslexia. Across both of the chronological age-matched comparisons, and the reading level-matched comparison, readers with dyslexia had longer total sentence reading times and made more fixations per sentence than typically developing readers. Typically developing readers were also significantly more likely to skip a word during reading than readers with dyslexia, and shorter mean fixation durations were observed in the older typically developing group compared to the older group with dyslexia. This pattern of differences, and the observation of global eye movement differences between readers with and without dyslexia at an equivalent reading level, strongly suggests that readers with dyslexia are atypical rather than delayed in their cognitive processing during reading, mirroring the findings of Experiment One.

Participant group differences were similarly observed in the local eye movement analyses. Across both chronological age-matched comparisons, typically developing readers demonstrated shorter reading times in all four local eye movement measures than the groups with dyslexia. Older readers with dyslexia also had significantly longer reading times in all four local measures than the younger group with dyslexia. The observation of longer reading times across local measures in the younger compared to the older group with dyslexia suggests that there may be differences in cognitive processing of the target words between these groups. Specifically, it would suggest that younger readers with dyslexia have greater difficulty cognitively processing target words than older readers with dyslexia. Interestingly, however, this difference was not observed in the comparison of older and younger typically developing readers, suggesting that these two groups are no different in their ability to cognitively process the target words. It would appear that, by the time readers in the younger typically developing group have reached roughly the age of 14, lexical processing may have reached asymptote. In comparison, faster reading times were observed in the older than the younger group with dyslexia, suggesting that cognitive processing continues to develop throughout the teenage years in dyslexia. It may be the case that typically developing readers have attained the necessary level of reading expertise to allow cognitive processing to be roughly adult-like by age 14, and continued reading exposure after this period does not result in significant developmental changes. For readers with dyslexia, however, whose reading ability is reduced relative to their typically developing peers at age 14, continued exposure to print does result in cognitive processing development.

It was found that participants had shorter reading times on items previewed by orthographically similar nonwords compared to those previewed by orthographically dissimilar nonwords. This suggests that parafoveal pre-processing of orthography is an important component of silent reading in teenage readers, as a greater degree of orthographic overlap between the preview and the target word facilitated lexical identification, as reflected in reduced fixation durations following orthographically similar previews. This effect did not vary by group; there were no significant differences in the way participants with and without dyslexia parafoveally pre-processed the orthographic characteristics of the preview nonwords. The same effect was observed when comparing older with younger readers, suggesting parafoveal pre-processing of orthography is an important component of silent reading across adolescent readers.

Finally, there was a significant effect of phonological condition. Target words previewed by pseudohomophones received shorter fixations than those previewed by spelling controls, suggesting that parafoveal pre-processing of phonology facilitated lexical identification of the target word upon its eventual fixation. It was predicted that groups with dyslexia would demonstrate reduced parafoveal pre-processing of phonology. No group by phonological condition interactions were observed, however, suggesting that all participants were similarly able to process the phonological characteristics of the preview in the parafovea.

The pseudohomophone effect in teenage readers. As mentioned in the Introduction, a number of studies have demonstrated that readers process phonological information in the parafovea during silent reading. Pollatsek et al. (1992) observed that homophonic previews (e.g., *beech* for the target word *beach*) led to shorter reading times on the target word than did nonhomophonic previews (*bench*), a finding also replicated by Chace et al. (2005). These findings clearly demonstrate that, for skilled adult readers, a word’s phonological representation is activated parafoveally, and suggests that this process may influence lexical identification. What is less clear, however, is how the ability to pre-process phonology develops, and at what age young readers are able to extract phonological information from the parafovea to facilitate lexical identification. On the basis of the evidence presented in this study, it is clear that younger readers do process the phonological characteristics of words prior to fixation, and suggests that parafoveal processing is already relatively sophisticated by roughly age 14. This was manifested in two separate findings. Firstly, no significant differences were observed between reading times on the target word following an identical preview (e.g., *summer-summer*) and an orthographically similar pseudohomophone preview (e.g., *summor*). This finding is conceptually similar to that observed in Experiment One, where reading times on correct target words and orthographically similar pseudohomophones did not differ. Secondly, there was a significant effect of phonological condition such that reading times on target words previewed by pseduohomophones were shorter than on those previewed by spelling controls. If participants did not parafoveally pre-processing phonology, the preview benefit observed between pseudohomophone and spelling control previews should be equivalent, as each differs orthographically from the correct target word to the same extent. Taken together, these findings very strongly suggest that young readers both foveally and parafoveally process phonology during silent reading.

Parafoveal pre-processing of phonology in dyslexia. Four potential patterns of eye movement behaviour with regard to parafoveal processing in dyslexia were outlined previously in this chapter. Firstly, it may be the case that readers with dyslexia do not parafoveally pre-process upcoming words whatsoever during silent reading, or do so to a limited extent relative to their typically developing peers. This is a fairly unlikely pattern of data as, whilst it could be expected that very young readers do not process information in the parafovea during reading, participants in the present study were teenagers and therefore likely to parafoveally pre-processing upcoming words to at least some extent. Secondly, readers with dyslexia may be unimpaired in their orthographic parafoveal processing, but may not parafoveally process the phonological characteristics of words due to the phonological processing deficits associated with dyslexia. Once again, this was not shown to be the case; all participant groups, both typically developing and with dyslexia, were able to pre-process both the phonological and orthographic characteristics of the preview nonword. This was reflected in shorter reading times on items previewed by pseudohomophones and orthographically similar previews. This was the third potential pattern of parafoveal processing that was outlined; that participants with dyslexia would be able to pre-process both the phonological and orthographic characteristics of the upcoming nonword during silent reading. The findings of this study provide evidence for the third pattern of effects described; that is, equivalent phonological processing in typically developing readers and readers with dyslexia.

As mentioned, no studies to date have examined the parafoveal processing of phonology during silent reading in dyslexia. Rayner (1986) observed that the perceptual span increases in extent as reading ability develop, and Chace et al. (2005) observed that less skilled adult readers demonstrated no evidence of parafoveal pre-processing of phonology during reading. Using the boundary paradigm, participants were presented with homophonic or nonhomophonic previews, and whilst a homophone preview benefit was observed in more skilled readers, this effect was not observed in less skilled readers. Chace et al. (2005) suggested that poor readers allocated greater processing resources to the foveal word, whereas more skilled readers were able to distribute processing resources more effectively across the sentence. Given the lack of phonological preview benefit among less skilled adult readers, it was somewhat surprising that all participants in the present study were similarly able to pre-process the phonological characteristics of the preview. It is necessary to examine the stimuli used by Chace et al. (2005) to address this difference in findings.

One key difference between the present study, and that of Chace et al. (2005) concerns the properties of the pretarget word in the sentences. Chace et al. (2005) used pretarget words of between five and eight letters, which were typically adjectives, with a mean frequency of 77 per million. In the interest of studying parafoveal processing, it is important to discard trials in which the pretarget word is skipped during first pass reading, and the use of longer, less frequent, pretarget words allows for fewer trials to be discarded during analyses. Whilst not explicitly mentioned by Chace et al. (2005), the probable reason for controlling pretarget words in this way is to minimise instances of the pretarget word being skipped. In the current study, longer pretarget words were not used due to the need to make both the correct target word highly predictable from the prior sentence context, and the sentence itself simple to comprehend for the readers with dyslexia. Recall that the conclusion of Chace et al. (2005) was that poor readers were required to allocate greater processing resources to the pretarget word, and were therefore less able to parafoveally pre-process the upcoming word compared to good readers. It may be the case that readers with dyslexia in the present study were more easily able to identify the currently fixated pretarget word, and that this facilitated parafoveal pre-processing, whereas this did not occur in the study of Chace et al. (2005).

A number of studies have demonstrated that the difficulty with which a reader processes the pre-boundary word affects the extent of parafoveal processing. For instance, Henderson and Ferreira (1990) manipulated the processing difficulty associated with the pretarget word by varying its frequency. Participants read target words (e.g., *despite*) following correct previews (*despite*) or incorrect previews (*zqdioyv*), and the pretarget word was frequent (e.g., *chest*) and infrequent (e.g., *trunk*). It was found that preview benefit was greater when the pretarget word was frequent, with the explanation that a lesser foveal load (i.e., the resources required to process the pretarget word) allowed for a greater degree of parafoveal processing to take place in skilled readers (see also, White, Rayner & Liversedge, 2005). These results suggest that the difficulty with which readers are able to process the pretarget word significantly influences the degree with which parafoveal processing takes place. The relatively short (mean: 4 letters, range: 2-6 letters) pretarget words used in the present study may have been simpler to process than the pretarget words used by Chace et al. (mean: 6 letters, range: 4-8 letters), thus allowing more parafoveal processing to be undertaken by the readers with dyslexia in this sample. Pretarget words in the present study also had a higher average frequency (18697 per million, Balota, et al., 2007) than those in the study of Chace et al. (2005; 77 per million), allowing faster processing to take place. It has clearly been demonstrated, however, that readers with dyslexia are capable of parafoveally pre-processing information to the right of fixation during reading.

An additional difference between stimuli in the present study and those of Chace et al. (2005) concerns semantic constraint. Recall that sentences were pre-screened to ensure that they were highly semantically constraining to the correct target word (see Chapter 3). It has previously been demonstrated that parafoveal pre-processing may be facilitated by the parafoveal word in a sentence being highly constrained within the sentence context (Balota, Pollatsek, & Rayner, 1985). This suggests that the context of the sentence being read affects the extent to which readers parafoveally pre-process the upcoming word, and it may be the case that the increased semantic constraint in the sentences used in the present study facilitated parafoveal processing to a greater extent than those used by Chace et al. (2005).

In summary, this study found no evidence to suggest differential parafoveal pre-processing of phonology between young readers with and without dyslexia. Across two chronological age-matched comparisons, and a reading level-matched comparison, all readers demonstrated shorter reading times on target words following a pseudohomophone preview than a spelling control. If readers with dyslexia were unable to pre-process phonology during silent reading, such an effect could not be observed. It may be the case, however, that the relative ease with which readers with dyslexia were able to process the pretarget word facilitated parafoveal processing.

Orthographic processing in dyslexia. Another interesting finding concerns the three-way interactions observed concerning the older group with dyslexia. Contrasts indicated that the older group with dyslexia demonstrated a significant pseudohomophone advantage only in instances where the preview was orthographically dissimilar to the correct target word. This is a somewhat counterintuitive finding, as across participant groups it was observed that reading times on target words following orthographically similar items were shorter than those following orthographically dissimilar items. A greater degree of orthographic overlap between the preview and the target word should facilitate lexical identification and result in shorter reading times on the target word. Instead the opposite effect was observed in this instance- previews with a lesser degree of orthographic overlap appeared to facilitate lexical identification to a greater extent than previews with more overlap. It is necessary to investigate the mean reading times to further understand why this effect may have been observed.

The older group with dyslexia demonstrated almost identical reading times on items previewed by orthographically similar pseudohomophones (263ms) and those previewed by orthographically dissimilar pseudohomophones (265ms) in first fixation duration. When reading items previewed by spelling controls, however, the differences based on orthographic similarity became much larger (245ms versus 312ms for orthographically similar and dissimilar previews respectively). The vastly inflated reading times on items previewed by orthographically dissimilar spelling controls appears to be the basis for the significant difference observed between pseudohomophones and spelling controls. Why, then, do these types of preview provide such a reduced benefit in terms of subsequent fixation duration in the older group with dyslexia? It may be the case that the three other types of preview are relatively facilitative to lexical identification in the group with dyslexia, as they are either phonologically congruent with the target word (Orthographically similar and dissimilar pseudohomophones), orthographically congruent with the target word (Orthographically similar pseudohomophones and spelling controls), or both. Orthographically dissimilar spelling controls are neither phonologically nor orthographically congruent with the target word, and it may be the case that the older group with dyslexia has more difficulty processing a target word following a preview that is not facilitative either phonologically or orthographically than the other participant groups. This account remains somewhat speculative, however, as this effect was not observed in the younger group with dyslexia.

Conclusion. Despite the indication from the pen and paper assessments of reading and phonological processing being that the participant group with dyslexia were impaired in their phonological processing ability, the present eye movement study found no evidence to suggest that readers with dyslexia were impaired in the parafoveal pre-processing of phonology. Across multiple comparisons, all participant groups demonstrated a pseudohomophone preview benefit during silent reading, very strongly suggesting that all participant groups processed the phonological characteristics of the upcoming nonword in the parafovea. On the basis of this evidence, it would appear that the way in which readers access the phonological representations of words during natural sentence reading may not significantly differ in dyslexia

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Chapter Six: General discussion

The studies outlined in this thesis aimed to investigate both phonological and orthographic processing in young readers with and without dyslexia during silent reading, and the extent to which these processes may interact. Few studies to date have used eye-tracking to monitor the moment by moment cognitive processes that underpin silent reading in young readers, and none have directly investigated phonological processing in this manner using participants with dyslexia. The subject of phonological processing during silent reading is important in this regard for at least two reasons, as outlined in Chapter One.

Firstly, prior research has demonstrated that skilled adult readers process the phonological characteristics of words and nonwords during silent reading, and there is some evidence to suggest that the processing of phonology aids lexical identification. The processing of speech sounds is, therefore, an important aspect of skilled reading, and the extent to which readers with dyslexia typically process phonology during silent sentence reading has not been directly investigated to date. Secondly, the phonological deficits hypothesis is a widely accepted theory for the reading difficulties associated with dyslexia. Specifically, according to this account, readers with dyslexia have difficulty with the storage, retrieval, and manipulation of speech sounds relative to their typically developing peers. This, in turn, hinders the learning of the relationship between written words and their phonological representations, an important process during reading development. The range of phonological difficulties that have been reported in readers with dyslexia was outlined in Chapter One, and, while alternative theories implicate a number of different primary impairments that lead to dyslexia, most suggest at least some role for phonological processing deficits. Investigating the role of phonological processing in dyslexia is, therefore, crucial to understanding how such deficits affect the process of silent reading.

6.1. Summary

In Experiment One, foveal processing of phonology and orthography was investigated in readers with and without dyslexia. As mentioned, it has been shown that skilled adult readers process phonology during silent reading. It was less clear, however, whether younger readers, either with or without dyslexia, pre-lexically process phonology during silent reading. Global group differences in eye movement behaviour were robustly observed between groups of readers with and without dyslexia, strongly suggesting cognitive processing difficulties associated with dyslexia. In local eye movement analyses, reading times on pseudohomophones and spelling control words were recorded, with the hypothesis that significantly shorter reading times on the former compared to the latter would be indicative of phonological recoding. The most striking finding from Experiment One was that this effect was consistently observed in all participant groups regardless of the more general reading difficulties previously established in the two groups with dyslexia. It was argued that this pattern of findings very strongly suggested that readers with dyslexia are able to rely on phonological recoding for lexical identification during silent reading, in a way that was not significantly different to their typically developing peers.

One explanation for this was related to the sentence reading task itself, and that the both the highly constraining nature of the sentences and the correspondence to a lexical entry facilitated identification of the pseudohomophone for readers with dyslexia in a way that was not possible in some prior studies. Prior research into phonological processing in dyslexia has frequently used single word or nonword stimuli and tasks with demands that may not be necessary during silent sentence reading (e.g., word naming, decision tasks). Whilst there is robust evidence to suggest that readers with dyslexia have phonological processing deficits, it was argued that these deficits may not impact upon phonological recoding during silent reading.

Whilst no evidence for differential processing of phonology was observed between typically developing readers and readers with dyslexia, a different pattern of results emerged concerning orthographic processing. All four participant groups demonstrated faster reading times on items in orthographically similar conditions, suggesting that a greater degree of orthographic overlap between a nonword and its corresponding real word is facilitative for identification of that word. This difference, however, was significantly greater in the older group with dyslexia.

The focus in Experiment One was largely on foveal processing, and to what extent readers with dyslexia were able to process the speech sounds of items whilst directly fixating them. What cannot be ascertained from this study was, therefore, to what extent readers with dyslexia are able to parafoveally pre-process phonology during reading. Parafoveal pre-processing is an important aspect of skilled reading, but little is known about the extent to which readers with dyslexia are able to pre-process the orthographic and phonological characteristics of words during silent reading. Given that a phonological preview benefit was not observed across all skilled adult participants in a previous study (Chace, Rayner, & Well, 2005), the hypothesis was that this sample of younger readers with dyslexia would not demonstrate a pseudohomophone preview benefit, indicating that readers with dyslexia do not parafoveally pre-process the phonological characteristics of words during silent reading. Once again, however, the findings clearly suggested that readers with dyslexia did phonologically pre-process upcoming target nonwords.

Taken together with the results of Experiment One, these findings demonstrate that readers with dyslexia are able to use phonological recoding for lexical identification during silent reading to an extent that does not significantly differ from typically developing readers. It was suggested that this effect may have been affected in part by the properties of the stimuli used in Experiment Two; highly predictable sentences and short pre-target words meant that the conditions for parafoveal pre-processing of the target nonwords to take place were facilitative. While these factors may account for differences between prior research and the present study, the findings reported here very convincingly demonstrated that readers with dyslexia were able to pre-process the phonology of upcoming letter strings. There was also evidence across both experiments to suggest differential orthographic processing in dyslexia. These results will be considered below with regards to influential accounts of dyslexia, reading acquisition, and the development of cognitive processing during reading.

6.2. Implications for the phonological deficits hypothesis

It is important to firstly state that, whilst the results reported in this thesis strongly suggest that readers with dyslexia process phonology during silent reading, the evidence for the phonological deficits hypothesis is broad. It is well established that readers with dyslexia are impaired in certain aspects of their phonological processing, as evidenced by many studies using a number of different paradigms. It may be the case that readers with dyslexia have additional auditory or motor impairments, but the presence of phonological processing difficulties in some form in dyslexia is widely accepted. Much of the evidence in favour of the phonological deficits hypothesis is, however, provided by tasks that introduce additional demands that may not be necessary for silent reading, and in particular focus upon phonological decoding, the effortful process of sounding out the phonological characteristics of words. Ramus and

Szenkovits (2003) have suggested that there are three aspects of the phonological deficit, and evidence for each is provided by tasks that introduce additional demands not necessary for silent reading or lexical identification. Firstly, readers with dyslexia have demonstrated an impairment in phonological awareness, as evidenced by poor performance in a range of tasks such as the ‘odd one out’ and phoneme and syllable counting tasks (Bruck, 1992; Bryant & Bradley, 1978). This suggests that readers with dyslexia may be less sensitive to the phonological structure of words. Secondly, readers with dyslexia have poor verbal short term memory (Hulme, 1981), suggesting that their ability to hold the phonological forms of words or nonwords in memory may be impaired. Finally, readers with dyslexia have slower lexical retrieval than typically developing readers, as exemplified by rapid automatized naming tasks (Denckla, 1976; Jones, Branigan, & Kelly, 2009). Many of these tasks involve either a verbal element (i.e., the participant must give a spoken response) or a choice-based element (participants must select a response from several possible responses), and it is unclear to what extent such tasks can be informative with regards to the cognitive processing that occurs during silent reading, in which lexical identification is supported by factors such as sentential context.

There were contrasting results from the pen and paper assessments and eye movement studies reported in this thesis. Readers with dyslexia were clearly impaired in their nonword decoding ability, and there was a trend towards these participants showing impaired performance in phonological processing. No evidence was found, however, to suggest that these phonological processing deficits impacted upon phonological recoding during silent reading. The groups with dyslexia demonstrated poorer reading ability that was not explained by lower IQ, and had global eye movement behaviour consistent with prior research into silent reading in dyslexia. It seems unlikely, therefore, that this sample of readers was unrepresentative of the impairments typically observed in dyslexia. Why, then, did these deficits not impact upon phonological recoding during silent reading?

The distinction between phonological decoding, the effortful process of sounding out the orthographic form of written words, and phonological recoding, an unconscious sublexical process whereby the phonological representation of a written word is accessed, may account for this pattern of effects. This is a nontrivial distinction, particularly when considering the evidence for a phonological deficit in dyslexia. As mentioned above, many of the tasks that have provided evidence for this hypothesis have used tasks that require phonological decoding, and indeed the nonword decoding task used in Experiments One and Two showed impaired performance in participant groups with dyslexia. This strongly suggests that readers with dyslexia are impaired in their ability to overtly manipulate the speech sounds of words. In a silent reading task, however, where readers may benefit from phonological recoding, there was no deficit observed in readers with dyslexia, suggesting that readers with dyslexia are able to undergo a developmental process as they learn to read whereby their decoding deficits are overcome for the purposes of lexical identification during silent reading. These deficits, however, persist in tasks that require overt phonological decoding.

It may also be the case that certain aspects of the stimuli used facilitated phonological recoding to some extent in readers with dyslexia, as discussed in Chapter Four. Firstly, the sentences used in each experiment were designed to be highly constraining to the correct target word, and this was confirmed through pre-screening procedures outlined in Chapter Three. Previous eye tracking studies (e.g., Ehrlich & Rayner, 1981; Rayner & Well, 1996) have indicated that supporting sentence context can facilitate identification of a word, and it may be possible that activation of the correct lexical entry was provided from the prior sentence context in the experiments reported here. Secondly, each misspelled word corresponded to a lexical entry in the sentence reading task, whereas there was no such correspondence between items in the pseudoword decoding task and lexical entries, a task in which deficits were observed in groups with dyslexia. Similarly, this may have aided phonological recoding in the sentence reading task, to an extent that reduced the impact of any impairments in readers with dyslexia.

To summarise, the presence of a pseudohomophone advantage across two experiments in readers with dyslexia does not necessarily invalidate the phonological deficits hypothesis. Rather, the distinction between phonological decoding, in which readers with dyslexia have been shown to be impaired in these and other experiments, and phonological recoding, which was not shown to be impaired in these experiments, may be important. On the basis of the evidence presented in this thesis, readers with dyslexia are able to develop sophisticated phonological recoding abilities, in spite of persistent deficits with phonological decoding. It will be vital for future studies to investigate how phonological recoding develops in dyslexia, and the phonological deficits hypothesis may have to better account for normal performance in certain phonological tasks in readers with dyslexia.

6.3. The relationship between phonological and orthographic processing

In each of the two experiments, there was some evidence to suggest that the processing of phonology during silent reading was impacted by the orthographic similarity of the nonword to its corresponding target word. In Experiment One, a significant interaction was observed between phonological and orthographic variables in first fixation duration, and in Experiment Two several three-way interactions indicated differential orthographic processing in the older group with dyslexia. Each of these patterns will be discussed.

Numerical trends within the data from Experiment One suggested that the pseudohomophone advantage was greater between items that were orthographically similar to the correct target word than those that were orthographically dissimilar. To account for this difference, it may be useful to consider models of word identification, and how they frame the relationship between the processing of phonology and orthography. One prominent model is the dual route cascaded model (Coltheart et al., 2001), which comprises two potential routes to word identification. The first, characterised as the lexical route, involves a direct lookup of a word in the reader's lexicon, in which both phonological and orthographic information are stored. The nonlexical route, by contrast, involves applying grapheme-phoneme correspondence rules grapheme by grapheme to words that are not stored in the lexicon. In Experiment One, participants directly fixated nonwords, which do not correspond to a lexical entry and, thus, cannot be identified via the lexical route. If participants were using the nonlexical route to identify the correct target word from its corresponding nonword, then a smaller pseudohomophone benefit should be observed for orthographically dissimilar items. Consider the orthographically dissimilar spelling control item *menro*. There was very little phonological overlap between this item and its corresponding correct target word *money*, and applying grapheme phoneme correspondence rules to this item would not facilitate identification of the correct target word. Applying these rules to the orthographically similar spelling control item *cheene*, however, would result in some phonological overlap, which may facilitate identification of the correct target word *cheese.* This could account for the greater pseudohomophone effect in orthographically similar items that may have more phonological overlap with their corresponding correct target word.

In both Experiments One and Two, there was evidence to suggest that the effect of orthographic similarity was more pronounced in the readers with dyslexia. These participants demonstrated a greater cost in terms of reading times on orthographically dissimilar items relative to orthographically similar items when compared to typically developing readers. The finding that readers with dyslexia are more disrupted in this regard suggests differential processing of orthography during silent reading in dyslexia. As discussed in Chapter One, Ehri (1992) suggested two processes contribute to changes in cognitive representations during reading development. Firstly, through continued exposure to print, the number of ‘word-specific’ representations continuously increases. These are commonly encountered words, the orthographic form of which may be more directly linked to semantic information, and less reliant on phonological processes to be lexically identified. Secondly, there is an increase in the quality of the connection between phonological and orthographic information at a phoneme and grapheme level- the learning of grapheme-phoneme correspondences. These two processes are facilitative of one another, and an impairment in one may be detrimental to the other. If young readers with dyslexia were less able to learn the specific correspondences between the written and spoken forms of words, it may lead to an overreliance on lexically identifying words from their orthographic form. As reading expertise develops through the course of formal literacy education, it may be the case that phonological processing abilities continue to improve, but an overreliance on the processing of the printed forms of words for their identification remains. This explanation remains speculative, however, as this effect was not observed in the younger group with dyslexia.

6.4. The development of cognitive processing during silent reading

Few studies to date have investigated the developmental trajectory in terms of eye movement behaviour during reading, and little is known about how cognitive processing continues to develop throughout the teenage years. Less still is known about this development in readers with dyslexia, or how it compares with typically developing readers. The studies reported here allowed the investigation of both global eye movement measures in younger and older readers, with and without dyslexia, and how they process phonology and orthography foveally and parafoveally during silent reading.

In typically developing readers

It is important to note that no differences were observed between older and younger typically developing readers in either orthographic or phonological processing, two important components of lexical identification. A reader's ability to process both the written forms and spoken sounds of nonwords, to lexically identify the companion target word, appears to be well developed by around age 14. Moreover, both groups demonstrated these abilities when processing nonwords both during and prior to direct fixation, suggesting that phonological and orthographic processing both foveally and parafoveally are important aspects of lexical identification during silent reading from this age. Given that these abilities did not differ between groups, it is important to further investigate why global eye movement differences were observed.

In terms of global eye movement behaviour, some age-related differences were observed between groups of younger and older readers. In both Experiments One and Two, younger typically developing readers had longer mean fixation durations than older typically developing readers, and in Experiment One the younger typically developing group made fewer fixations per sentence. As mentioned in Chapter Four, prior research on the development of eye movement behaviour during reading has suggested that, by age 12, eye movements are roughly adult like. It seems unlikely that there is no change to cognitive processing abilities between this age and adulthood, but the fact that significant differences were observed between readers who were, on average, just four years apart in chronological age suggests that readers at this age continue to undergo significant development with regards to cognitive processing during reading,

Chall (1983) has suggested that after a child has progressed beyond effortful decoding strategies that characterise the period of learning to read, they enter a stage of 'reading to learn', in which reading ability continues to develop in order to learn new information presented to them through the remainder of their education. Continued exposure to print helps to build vocabulary incidentally (Herman, Anderson, Pearson, & Nagy, 1987; Jenkins, Stein, & Wysocki, 1984), and may also help to develop cognitive representations of words to become better specified. The group differences observed in certain global eye movement behaviour measures may be a reflection of the older typically developing group's greater exposure to print, which in turn leads to better specified cognitive representations of words.

Similarly, and as outlined in Chapter Four, typical developments in cognitive processing can be linked to the lexical quality hypothesis (Perfetti & Hart, 2002). As readers continue to develop reading expertise, their cognitive representations of words become more fully specified in terms of the relationship between phonological, orthographic, and semantic aspects of words. Whilst the experiments reported here did not include any direct measure for lexical quality, it may be the case that the age-related changes in eye movement behaviour during reading are related to the continued development of cognitive representations of words.

In readers with dyslexia

Little is known about the development of cognitive processing during reading in dyslexia. Prior studies (see Kirkby, Webster, Blythe, & Liversedge, 2008, for a review) have indicated that readers with dyslexia are impaired in many global eye movement measures relative to chronologically age-matched participants, a finding further affirmed by the results reported here. As mentioned, how cognitive processing that occurs during reading develops in dyslexia is less well understood. Two patterns of differences seem plausible; firstly, that readers with dyslexia have an initial reading impairment relative to typically developing readers that does not improve over time with continued reading experience. In this instance, whilst reading ability does increase over time in dyslexia, the rate of reading development is no faster than in typically developing peers, and any reading deficit between a reader with and without dyslexia remains proportionally similar. Alternatively, it may be the case that initial reading difficulties that emerge in younger readers with dyslexia gradually improve to a level that, whilst remaining significantly below that expected for a typically developing reader, is less severe relative to their typically developing peers.

These results do not appear to suggest that cognitive processing differences between readers with and without dyslexia lessen as they get older and continue to gain greater exposure to printed words. Global eye movement differences were observed between both older and younger participant groups with and without dyslexia matched for chronological age. That is not to say, however, that cognitive processing does not continue to develop in readers with dyslexia; these results clearly demonstrate that, throughout the teenage years, readers with dyslexia continue to undergo significant changes in their cognitive processing during reading. It is, of course, difficult to identify the factors that influence these improvements, but, as in typically developing readers, continued exposure to print may help to develop better specified cognitive representations of words. It may also be the case that remediation that occurs during this period improves reading ability.

6.5. Conclusion

The findings reported here have clearly demonstrated that phonological processing deficits typically observed in dyslexia may not impact upon phonological recoding that occurs as part of lexical identification in silent reading in the same way that they impact upon performance in non-reading tasks. There was also evidence to suggest that readers with dyslexia may rely on orthographic processing to a greater extent than typically developing readers, their overreliance perhaps a long term result of impaired phonological processing abilities at an earlier stage of reading development.

Appendix A

Appendix A: Experimental Stimuli

Experiment One: Orthographically similar items.

When mum cooks pasta I like grated cheese/cheeze/cheene on top of it

The vicar prayed in the old church/cherch/charch every day even though it was cold.

Because he is in charge, we followed our scout leader/leeder/leuder up the hill.

A baby dog is called a puppy/puppi/puppa and is very small and cute.

The knight used a sword and shield/sheeld/shueld to fight in the battle.

Jane wore tights under her mini skirt/skert/skart at the party.

Sunshine is warm in the spring and hot in the summer/summur/summor normally.

The door was locked so I climbed in through the window/windoe/windou last night.

There are twelve months in every year/yeer/yeor and these make four seasons.

Rudolph the reindeer has a red nose/noze/nove unlike the others.

My brother is a soldier in the army/armi/armo but he came home for Christmas.

You can get rid of mistakes in pencil with the rubber/rubbur/rubbir on the end.

Experiment One: Orthographically dissimilar items.

Winne the Pooh loves to eat honey/hunni/henma straight out of jars.

Lisa likes to drink fresh orange juice/jooce/jeece with her breakfast every day.

We paid the man a lot of money/munni/menro to clean all the windows.

When the lady marries the king, she will become the queen/kween/treen tomorrow.

I had an ice cream yesterday and poured chocolate sauce/sorce/sunce over it.

Gareth threw the rugby ball/borl/newl to his friend who caught it.

Alex we outside to make a phone call/kawl/tarl because it was noisy inside.

The bus driver beeped his horn/hawn/hemn to let us know he was there.

I tried to draw a perfect round circle/sercle/norcle but it was hard.

We visited a pottery and made mugs out of wet clay/kley/bloy this morning.

If you eat an apple, most people throw the core/korr/borz away afterwards.

At the building site they lifted the bricks with a tall crane/krain/drauv today.

Experiment Two: Orthographically similar items

Cheddar is my favourite kind of cheese/cheeze/cheene to have for lunch.

My sister got married in an old stone church/cherch/charch in Scotland.

We were taught to tie knots by our scout leader/leeder/leuder tonight.

We got our dog when she was a tiny puppy/puppi/puppa a long time ago.

The knight carried his sword and shield/sheeld/shueld when we went into battle.

Lisa wore trousers instead of her skirt/skert/skart when she went out.

We have a school holiday when it is hot in the summer/summur/summor which I love.

The curtains were closed behind the broken window/windoe/windou last night.

I am just 13 now so I will become 14 next year/yeer/yeor on my birthday.

The friendly dog sniffed me with his wet nose/noze/nove and it tickled.

Dad fought in a war because he was a soldier in the army/armi/armo years ago.

On the end of my new pencil is a pink rubber/rubbur/rubbir which I use a lot.

Experiment Two: Orthographically dissimilar items.

Cows make milk and bees make honey/hunni/henma which tastes nice.

It is healthier to drink fruit juice/jooce/jeece than fizzy pop.

I decided to buy some sweets with my pocket money/munni/menro this week.

People cheered for the king and queen/kween/treen as they waved from the window.

The chips were nice when I squeezed lots of brown sauce/sorce/sunce over them.

My uncle hit the golf ball/borl/bewl hard and it went right over the hill.

I used my mobile phone to make a quick call/kawl/tarl to my friend.

My dad sits in his car and beeps the horn/hawn/hemn when he is ready to go.

I drew around a plat to make a perfect circle/sercle/norcle for my picture.

To make a pot, the artist used some wet clay/kley/bloy in which workshop.

Apple pips are in the middle bit, called the core/korr/borz that you don't eat.

The men lifted the car onto the lorry with a big crane/krain/drauv today.

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