UNDERSTANDING DYSLEXIA BY MEASURING EYE-MOVEMENTS DURING READING

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Dyslexia has been causally linked to both phonological deficits (Snowling, 2000) and difficulties in allocating attention (Valdois, Bosse, & Tainturier, 2004; Vidyasagar, 1999; Whitney & Cornelissen, 2005), both of which are utilised during parafoveal processing (Schotter, Angele, & Rayner, 2012). Whilst dyslexic readers have been found to display disruption in oculomotor control relative to skilled readers (Kirkby, Webster, Blythe, & Liversedge, 2008), there is a lack of research examining dyslexic parafoveal processing during reading. The experiments presented throughout this thesis examined whether parafoveal processing is less efficient for dyslexic readers compared to non-dyslexic readers (Jones, Ashby, & Branigan, 2013), and, explored the nature of dyslexic eye movement behaviour by including both a chronological-age and a reading-age matched control group. In three silent sentence-reading experiments, eye movements were recorded from dyslexic and non-dyslexic readers. Using the boundary paradigm (Rayner, 1975), parafoveal previews were either manipulated orthographically or phonologically. The results of these experiments indicated that readers with dyslexia gain parafoveal preview benefit during reading. Dyslexic children and adults demonstrated orthographic parafoveal preview benefits and encoded letter identity independently of letter position. Dyslexic readers did, however, show a specific dyslexic deficit in which they required a greater dependence on letter position information for lexical activation. When examining phonological preview benefits, neither dyslexic nor non-dyslexic readers showed a significant benefit for phonological pre-processing. All three experiments provided evidence that dyslexic readers demonstrated differential eye movement patterns to non-dyslexic readers. Dyslexic readers required additional fixations, longer gaze durations and total reading times even when compared to non-dyslexic readers matched on reading age. Taken together, the results indicate that dyslexic eye movement behaviour is not purely indicative of their reduced reading skill and is due to a specific dyslexic reading deficit. These findings are consistent with both phonological and attention deficit theories of dyslexia and indicate that dyslexic readers rely upon a serial sublexical grapheme–phoneme conversion method of reading (Hawelka, Gagl, & Wimmer, 2010).

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Declaration of Authorship

I hereby declare that the work presented in this thesis has not been and will not be, submitted in whole or in part to another University for the award of any other degree.

Signature:

Chapter One: Introduction

1.0 Chapter overview

This chapter provides an overview of the literature in relation to developmental dyslexia and theories of dyslexia. The focus then shifts to explaining eye movement behaviour during reading, providing an overview of both foveal and parafoveal processing for skilled readers, developing readers, and readers with dyslexia. The aims of the thesis are then outlined within a summary of the chapter.

1.1 What is dyslexia?

Reading plays a vital role in modern society; much of the teaching provided at school requires children to read and approximately 90% of all careers require literacy skills (Lenhard, Lenhard, & Breitenbach, 2005). As such, reading difficulties can have a considerable impact on a child's development as well as their future prospects (Peterson & Pennington 2015). Developmental dyslexia, one of the most common learning disabilities, is a lifelong reading disability suggested to affect between 5 and 17% of children (Shaywitz, 1998). Developmental dyslexia (from here on in referred to as dyslexia) is typically diagnosed when a child shows a persistent difficulty in learning to read that cannot be explained by a lack of general intelligence, motivation, sensory deficits or inadequate schooling (Shaywitz, 1998); dyslexia typically manifests as difficulties in learning to read accurately and with adequate speed. In fact, the fifth version of the American Psychiatric Association's Diagnostic and Statistical Manual (5th ed.; DSM-5; American Psychiatric Association [APA], 2013) refers to dyslexia as "*a pattern of learning difficulties characterised by problems with accurate or fluent word recognition, poor decoding and poor spelling abilities"* (p. 67). Indeed, dyslexia is specifically characterised by impaired decoding skills - the ability to map phonology (speech sounds) to orthography (printed letters; Snowling & Hulme, 2012).

In order to receive a diagnosis of dyslexia an individual must not only show difficulties with accurate or fluent word recognition, poor decoding and poor spelling, but must also demonstrate that *"the affected academic skills are substantially and quantifiably below those expected for the individual's chronological age"* (American Psychiatric Association, 2013, p. 67). This is usually determined through standardised achievement measures and comprehensive clinical assessment. In addition, it needs to be determined that *"the learning difficulties are not better accounted for by intellectual disabilities, uncorrected visual or auditory acuity, other mental or neurological disorders, psychosocial adversity, lack of proficiency in the language of academic instruction, or inadequate educational instruction"* (American Psychiatric Association, 2013, p. 67). Due to the above diagnostic criteria, dyslexia is typically diagnosed after children have had some formal education (approximately around the age of 9 years old). There are, however, a range of precursors for dyslexia that can be seen in children much younger than 9 years old, and also occasions where dyslexic difficulties only manifest later in an individual's academic career.

Children can start to show dyslexic tendencies as young as preschool age (Boets et al., 2011; Pennington & Lefly, 2001; Scarborough, 1990; Snowling, Gallagher, & Frith, 2003). These tendencies may be delayed speech, speech problems such as mispronunciations, struggling to remember the right words and put words together correctly, problems with rhyming, and difficulties in learning letters of the alphabet. As children get slightly older and start learning literacy skills at school they often present difficulties such as: problems learning the names and sounds of letters, accidental reversing of letters and numbers, slow and poor reading and writing, difficulty spelling and copying written text, visual disturbances (such as letters moving or appearing blurred), problems with sequencing (such as following directions or learning days of the week) and also poor phonological skills. Finally, as teenagers and adults, dyslexia tends to manifest as poor organisation within their written work, difficulties in taking notes or copying, poor spelling, memory difficulties and poor reading fluency. In fact, even when sufficient word reading accuracy is achieved, adults with dyslexia often still struggle with fluency deficits (Fletcher, Lyon, Fuchs, & Barnes, 2007). Indeed, it is possible for dyslexia to go undiagnosed during childhood, as difficulties may not fully manifest until the demands on reading surpass the individuals limited abilities. As such, dyslexic readers can go unnoticed during school, but be diagnosed later in life when academic demands are increased (for example, at university). Due to the changes in dyslexic characteristics, it is important to understand whether similar behaviours are present throughout the life span. To this end, the current thesis explores both adult and child dyslexic readers, in order to further understand how dyslexia may impact reading throughout development.

Whilst behavioural indicators of dyslexia may change throughout development, diagnosis of dyslexia largely relies upon the presence of difficulties in decoding and accurate or fluent reading. Dyslexia is, however, considered a heterogeneous condition in which individuals show a range of difficulties and variability within these difficulties (e.g. Hynd & Cohen, 1983). In fact, although a wide range of behavioural studies have reported dyslexic difficulties synonymous with the diagnostic criteria of dyslexia (such as decoding or phonological difficulties, and difficulties in accurate or fluent reading: Blachman, 2000; Fletcher et al., 1994; Shankweiler, Liberman, Mark, Fowler, & Fischer, 1979; Share & Stanovich, 1995; Stanovich & Siegel, 1994; Snowling, 2000; Torgesen, Wagner, & Rashotte, 1994; Vellutino, 1979, 1987; Vellutino, Fletcher, Snowling, & Scanlon, 2004; Vellutino & Scanlon, 1987a, 1987b; Vellutino, Scanlon, & Chen, 1995; Vellutino, Scanlon, & Spearing, 1995; Vellutino, Scanlon, & Tanzman, 1994; Vellutino et al., 1996; Wagner & Torgesen, 1987; Wagner, Torgesen, & Rashotte, 1994), there is also a body of research to support additional visual, attentional, auditory, and motor deficits within dyslexia. Specifically, dyslexic readers are reported to show deficits in rapid naming (Jones, Ashby, & Branigan, 2013; Jones, Branigan, Hatzidaki, & Obregon, 2010; Jones, Obregon, Kelly, & Branigan, 2008; Lervåg & Hulme, 2009; Moll & Jones, 2013; Parrila, Kirby, & McQuarrie, 2004; Powell, Stainthorp, Stuart, Garwood, & Quinlan, 2007; Wolf & Bowers, 1999), poor short-term memory or working memory (Ackerman & Dykman, 1993; Cohen, Netley, & Clarke, 1984; Gould & Glencross, 1990; Griffiths & Snowling, 2002; Jorm, 1983; McLoughlin, Fitzgibbon, & Young, 1994; Miles, 1993; Nelson & Warrington, 1980; Palmer, 2000; Rack, 1985; Roodenrys & Stokes, 2001; Rose, Feldman, Jankowski, & Futterweit, 1999; Smith-Spark, Fisk, Fawcett, & Nicolson, 2003; Swanson, Ashbaker, & Lee, 1996), slower visual search (Buchholz & McKone, 2004; Casco & Prunetti, 1996; de Boer-Schellekens & Vroomen, 2012; Iles, Walsh, & Richardson, 2000; Lallier, Donnadieu, & Valdois, 2013; Vidyasagar & Pammer, 1999), a reduced visual attentional span (Bosse, Tainturier, & Valdois, 2007; Valdois, Bosse, & Tainturier, 2004), poor coherent motion detection (Cornelissen, Richardson, Mason, Fowler, & Stein, 1995; Cornelissen et al., 1998; Pammer & Wheatley, 2001), contrast sensitivity (Borsting et al., 1996; Lovegrove, Bowling, Badcock, & Blackwood, 1980; Lovegrove et al., 1982; Martin & Lovegrove, 1984,1988), poor frequency discrimination (Ahissar, Protopapas, Reid, & Merzenich, 2000; McAnally & Stein, 1997), and clumsiness (Fawcett & Nicolson, 1995, 1999; Orton, 1937;

Snowling, 2000). Furthermore, and in line with the heterogeneity of dyslexic characteristics, there are a number of alternative theories of dyslexia. The most widely accepted and researched theories will be discussed in further detail below.

1.2 Theories of dyslexia

1.2.1 The Phonological Deficit Hypothesis

To date, the most widely accepted theory of dyslexia is the Phonological Deficit Hypothesis (Liberman, 1973; Snowling, 1995, 2000; Stanovich, 1988). This theory purports that dyslexia occurs as a consequence of cognitive deficits in accessing, manipulating, and storing phonological representations. Consequently, individuals with dyslexia are often shown to have difficulties in tasks that require phonological awareness. Such tasks include: associating letters with the correct speech sounds (grapheme-phoneme correspondence; Snowling, 1995, 2000; Stanovich, 1988), detecting and discriminating differences in phonemes, and breaking words down into their constituent sounds (i.e. phoneme deletion tasks; Bruce, 1964; McDougall, Hulme, Ellis, & Monk, 1994). Phonological awareness deficits cause difficulties in sound segmentation and blending, both of which are critical in the development of reading and spelling (Bradley & Bryant, 1983). In addition, deficits in accessing phonological representations may impair the ability to store high-quality representations of word spellings, which, consequently, affects rapid word identification and reading fluency (Hulme & Snowling, 2013; Lervåg & Hulme, 2009). The Phonological Deficit Hypothesis (Liberman, 1973; Snowling, 1995, 2000; Stanovich, 1988) postulates a straightforward link between a cognitive level deficit and the observed behavioural characteristics; however, this argument has been described as circular (Vidyasagar & Pammer, 2010; Stein, 2018a, 2018b) as phonological deficits are used as a defining characteristic of dyslexia as well as a cause to explain their reading difficulties.

There has, nevertheless, been much research to support the Phonological Deficit Hypothesis of dyslexia (Vellutino et al., 2004). Firstly, there are numerous studies which report that dyslexic readers perform poorly on phonological awareness and letter-sound decoding tasks compared to skilled readers (e.g. Blachman, 2000; Fletcher et al., 1994; Shankweiler et al., 1979; Share & Stanovich, 1995; Stanovich & Siegel, 1994; Snowling, 2000a; Torgesen et al., 1994; Vellutino, 1979, 1987; Vellutino & Scanlon, 1987a, 1987b; Vellutino et al., 1994; 1995a; 1995b, 1996, 2004; Wagner & Torgesen, 1987; Wagner et al., 1994). Secondly, phonological awareness is crucial for accurate and fluent reading for typically developing readers. Thirdly, phonological awareness in young children has been shown to predict their future reading ability (Bradley & Bryant, 1983) and is a stronger predictor than deficits in rime awareness, verbal short-term memory and word reading skill (Melby-Lervåg, Lyster, & Hulme, 2012). Finally, although many of the studies that link phonological deficits with reading difficulties have been correlational or cross-sectional studies (Melby-Lervåg et al., 2012), intervention studies have also provided evidence to support a causal role of phonological deficits in reading difficulties (Bradley & Bryant, 1985). When beginning readers are given phonological training, they show marked improvements in word identification, spelling and general reading ability (Bradley & Bryant, 1985), regardless of their general intelligence (intelligence quotient, IQ; Hatcher & Hulme, 1999). Consequently, it is largely accepted that phonological skills play a key role in the development of reading skills for all child readers (Vellutino et al., 2004). It is, however, important to note that phonological skills appear to be a stronger predictor of reading ability in general than of reading disability specifically (Scarborough, 1998).

Additional evidence for a causal role of phonological deficits in dyslexia has been provided by behavioural, genetic and neuroimaging studies (see Pennington & Olson, 2005, for a review; Snowling, 2000). Furthermore, a growing body of evidence supports phonological deficits in alphabetic languages, but, also in different orthographies such as Chinese, a logographic language (Ho, Chan, Lee, Tsang, & Luan, 2004; McBride-Chang et al., 2008). Thus, there is a large amount of data to support the role of phonological deficits in dyslexia.

As described above phonological deficits are generally considered to play a considerable role in causing dyslexia, however, it must be noted that not all readers with dyslexia exhibit phonological deficits. Some dyslexic readers can perform within normal parameters on tasks where the Phonological Deficit Hypothesis would predict poor performance (Ramus & Ahissar, 2012). Furthermore, individuals with dyslexia do not always demonstrate phonological deficits (e.g. Castles & Coltheart, 1996; Frederickson & Frith, 1998; Pennington et al., 2012; Valdois et al., 2011) and not all individuals with phonological deficits have dyslexia (e.g., Catts & Adlof, 2011; Howard & Best, 1996; Snowling, 2008). For the reasons discussed above, theories based upon the notion of a single phonological deficit have often been regarded as incapable of explaining the entire phenotype of this highly heterogenic learning disability (Pennington, 2006; Ramus & Ahissar, 2012).

In fact, much of the research into phonological deficits has focused upon the phonological aspects of decoding. Decoding is, however, the ability to map phonology to orthography (Snowling & Hulme, 2012); as such, some researchers have considered the role of orthographic encoding in reading difficulties (Castles & Coltheart, 2004) rather than solely focusing upon the phonologic aspects. Indeed, there is evidence to show that phoneme awareness tasks are influenced by the properties of the corresponding orthographic representation (Castles, Holmes, Neath, & Kinoshita, 2003; Stuart, 1990; Treiman & Cassar, 1997). Deficits in phonological tasks may, therefore, be influenced by difficulties with both letter-based orthographic information as well as sound-based phonological information. In which case, Castles and Coltheart (2004) propose it may be more accurate to consider dyslexia as a deficit that occurs from a failure to form satisfactory grapheme-phoneme correspondences. Such a deficit may arise from difficulties with processing graphemes - the visual counterpart of the word, specifically, or from problems in forming the correct visual-auditory associations between the graphemes and the phonology. Phonological decoding is an attention-demanding process (Reynolds & Besner, 2006) and requires both phonological skills (Ramus, 2003; Ziegler & Goswami, 2005) and efficient allocation of visual attention (Cestnick & Coltheart, 1999; Facoetti et al., 2006; Perry, Ziegler, & Zorzi, 2007). There are, therefore, a range of skills such as visual attention and orthographic encoding that also play an important role in decoding.

Finally, one of the major weaknesses of the Phonological Deficit Hypothesis has been its inability to explain the occurrence of subtle sensory and motor deficits often characteristic of dyslexia (Stein, 2018a; Stein, 2018b). Those who support the theory typically dismiss sensory and motor deficits as features that are not part of the core profile of dyslexia (e.g. Snowling, 2000). There are, however, other theories that consider the sensory and motor deficits in readers with dyslexia to be core and therefore endeavour to explain such deficits (Hari & Renvall, 2001; Vidyasagar, 1999). As such, the following section will explore theories of dyslexia that attempt to explain the broader dyslexic profile.

1.2.2 The Magnocellular Theory

The magnocellular theory, an alternative and somewhat more controversial theory of dyslexia, considers dyslexia to occur as a result of impairment within the visual pathways, rather than a phonological or linguistic difficulty (Stein, 2001; Stein, 2018a). In this proposal, dyslexic readers have abnormalities within the magnocellular stream of the visual system and this, in turn, causes a range of visual, auditory, attentional and motor difficulties that casually impact on reading ability (Stein, 2018b). Although an in-depth review of the physiology of the visual system is beyond the scope of the current research, a brief explanation of the visual systems and in particular the magnocellular stream, is provided below in order to explain how deficits within magnocellular functioning may impact reading. See Figure 1.1 for an overview of the anatomy of the visual pathways in the visual system (Boden & Giaschi, 2007).

The subcortical human visual system is thought to consist of at least two parallel pathways, the parvocellular (P stream) and the magnocellular (M stream; for a review see Milner & Goodale, 1995). These streams begin at the retina (a light sensitive layer at the back of the eye which is built up of photosensitive cells that convert light energy into signals) where both magnocellular neuron and parvocellular neuron ganglion cells are present. Magnocellular neurons respond and conduct signals more rapidly than parvocellular neurons, they are more sensitive to temporal change within the environment (such as flickers of movements) and are particularly important in capturing attention. Magnocellular neurons provide the main signal for visual guidance of both attention and eye and limb movements. In addition, magnocellular neurons are known to direct the parvocellular neurons to each letter, in order to identify it and its position within a word. Parvocellular neurons define colour and detail, are key for reading and provide the main input into the visual word form area (VWFA) where letters are identified. It is generally accepted that the magnocellular system is involved in the processing of temporal change and low-contrast information and is tuned to low spatial frequencies, whereas the parvocellular system is involved in the processing of chromatic information and is tuned to low temporal and high spatial frequencies.

Magnocellular and parvocellular neurons project to separate layers in the primary visual cortex, V1 (See Figure 1.1; Baizer, Ungerleider, & Desimone, 1991;

Livingstone & Hubel, 1988; Maunsell, Nealey, & De Priest, 1990). Therefore, the two streams are processed separately up until this point. From V1, there is a mingling of the magnocellular and parvocellular streams, but the anatomical segregation is at least partially maintained in the next visual area, V2 (DeYoe & Van Essen, 1988; Ferrera, Nealey, & Maunsell, 1992; Lennie, Trevarthen, Van Essen, & Wassle, 1990; Shapley, 1990). From then on, there are two streams that project the visual information to the rest of the brain, the dorsal stream and the ventral stream.

The magnocellular neurons provide the main visual input to the dorsal pathway (considered to process "where" and "when" information), which connects V1 to the posterior parietal lobe. The dorsal stream comprises several cortical areas such the medial temporal area (MT or V5), media superior temporal area (MST) and

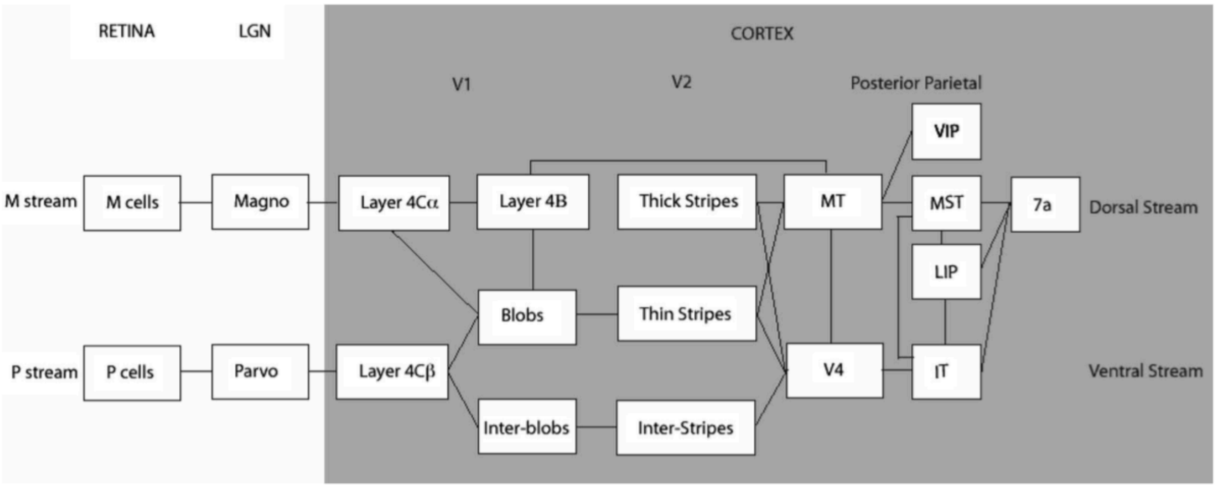

Figure 1.1. Anatomy of parallel pathways in the visual system of a monkey. LGN, lateral geniculate nucleus of the thalamus; V1, cortical visual area 1; V2, cortical visual area 2; V4, cortical visual area 4; M, magnocellular; P, parvocellular; MT, medial temporal area; VIP, ventral intraparietal lobe; MST, medial superior temporal area; LIP, lateral intraparietal cortex; IT, inferior temporal cortex; 7a, area 7a of the parietal cortex. Reprinted from "M-stream deficits and reading-related visual processes in developmental dyslexia", by C. Boden and D. Giaschi, 2007, Psychological bulletin, 133(2), p. 348. Copyright 2007 by the American Psychological Association.

the ventral and lateral intraparietal areas (VIP; LIP). This stream mediates the visual guidance of attention and eye and limb movements and has also been implicated in object localization, motion perception, goal-directed movements and appears to mediate selective visual attention (Posner, 1995). Parvocellular neurons provide the main input to the ventral ("what") pathway, which connects V1 to the inferotemporal region. The ventral pathway continues from V1 and V2 into V3 and V4 and is known for detecting texture, form and colour of objects. The VWFA lies within the parvocellular pathway, which passes ventrally underneath the occipitotemporal cortex.

The above description of the magnocellular stream is useful in order to understand that deficits within the M stream may occur at any point between the retina and the dorsal stream, and, consistent with Boden and Giaschi (2007), this document will discuss the magnocellular and parvocellular systems as the M stream and P stream, as deficits may occur anywhere throughout these systems. The above description is also useful in order to consider how deficits in the magnocellular stream may impact more specifically upon reading, eye movements and visual attention.

The magnocellular theory of dyslexia has been proposed based upon neuroscientific evidence that shows that many people with developmental dyslexia also show low-level problems in visual processing (see Farmer & Klein, 1995; Klein, 2002, for reviews) and that these low-level visual difficulties (such as perception of flicker and motion) are considered to arise from abnormalities in a part of the M stream (reviewed in Stein, 2001). Therefore, the theory purports that dyslexic readers have difficulties in reading that occur because of their M stream deficits (Stein, 2018a, 2018b). Indeed, this theory has been adapted and extended to include auditory, motor, and the phonological deficits characteristic of dyslexia. There has, however, been much debate about the role of the magnocellular system in dyslexia (Blythe, Kirkby, & Liversedge, 2018; Skottun, 2000, 200). Specifically, Skottun (2000; 2001) questioned the magnocellular theory on two counts: (a) it is unclear whether the M stream is important to reading and (b) M-stream deficits, if they exist, may not be the cause of the reading difficulties seen in dyslexia. These issues have been somewhat addressed by Boden and Giaschi (2007) who identified and investigated possible roles for the M stream in reading, with focus upon the visual modality.

Although deficits in motion perception tests are often used to determine poor magnocellular functioning (Boden & Giaschi, 2007; Skottun & Skoyles, 2007; Stein, 2001), other characteristics of the M stream, such as good contrast sensitivity and fast neural transmission speeds, are potentially more relevant to reading. Furthermore, deficits in the subcortical M-stream function may lead to altered dorsal stream processes, which can cause problems with visual selective attention and eye movements. It is these latter functions that are an integral part of reading and of great interest in this thesis. Consequently, Boden and Giaschi (2007) proposed the following hypothesis to explain how magnocellular dysfunction may cause reading difficulties: 1) reduced contrast sensitivity at low spatial frequencies may interfere with the visual analysis of the features that make up the word; 2) poor spatial localisation may cause problems with position encoding of letters within a word; 3) an unstable reference (dominant) eye or poor vergence control may result in unstable binocular coordination; 4) deficient posterior parietal lobe functioning may cause attentional difficulties when focusing on the fixated word and/or orienting to the next word; 5) temporal precedence of global information about parafoveal words may be disrupted; 6) deficits in the processing of location information may lead to problems programming saccadic eye movements; 7) the inability to adequately suppress visual information during a saccade could create smearing during reading.

It is, understandable that all the above deficits may lead to reading difficulties. However, as discussed within their paper (Boden & Giaschi, 2007), several of these hypotheses have been already been addressed (e.g., Kirkby, Blythe, Drieghe, & Liversegde, 2011). Furthermore, a number of these hypotheses are in fact closely related and largely rely upon efficient attention. As discussed in Boden and Giaschi (2007), Cornelissen, Hanson, Hutton, Evangelinou and Stein (1998) proposed that an M-stream deficit might create confusion about the where letters are positioned within words (spatial localization). Poor spatial localisation may occur as a result of M stream deficits because the posterior parietal lobe is important for attentional processes such as encoding spatial position (Husain, 1991). Indeed the ability to encode spatial position is dependent on efficient attention allocation (e.g. Cornelissen, Hansen, Gilchrist, et al., 1998; Vidyasagar, 2001, 2004) and can be considered as a micro-level effect of an attention deficit. In contrast, *deficient posterior parietal lobe functioning may cause attention difficulties when focusing on the fixated word and/or orienting to the next word*, can be considered a macro-level effect of an attention deficit affecting attentional distribution across words. Such deficits would impact a reader's ability to adequately encode letter position information within a word and also to encode useful information from the next word. There is rising interest in attentional deficits associated with dyslexia and a number of attentional theories have been proposed. Some of these theories are in line with the magnocellular theory, whereas others like to dissociate from deficits in magnocellular functioning. The following section will discuss attention deficit theories.

1.2.3 Attentional Theories

There are a number of different accounts of how dyslexia is caused by attention deficits, one such account is the *Sluggish Attentional Shifting* (SAS) Hypothesis (Hari & Renvall, 2001; Lallier, Donnadieu, Berger & Valdois, 2010). The SAS Hypothesis was developed to explain the subtle sensory and motor deficits that occur in dyslexia synonymous with the magnocellular deficit theory (Stein, 2001). SAS builds upon the magnocellular proposal that deficits in parietal lobe functioning may result in deficient attention and thus cause temporal processing impairments in dyslexia (Stein & Walsh, 1997). According to this hypothesis, individuals with dyslexia struggle to disengage attention when visual or auditory stimuli are presented within a rapid sequence; attention is 'sluggish' and engaging and disengaging attention takes longer for a dyslexic reader than a typical reader (Hari & Renvall, 2001). This *Sluggish Attentional Shifting* then results in readers with dyslexia having a prolonged 'cognitive window', 'time' or 'input chunk' (i.e. time it takes the readers to process information; Hari, & Kiesilä, 1996; Helenius, Uutela, & Hari, 1999; Merzenich, Schreiner, Jenkins, & Wang, 1993). These increased processing durations are said to cause confusion with the temporal order of successive items (Hari & Renvall, 2001) and distort the development of correct phonological representations required for reading acquisition.

The SAS hypothesis considers deficits in attention to fall specifically within serial attention allocation; whereby serial identification of letters is more challenging for those with dyslexia than for typical readers. This is supported by studies showing impaired serial visual identification (Ruffino et al., 2010) and slower spatial cuing (Facoetti et al., 2010) among dyslexic children. Indeed, evidence for the SAS hypothesis has been found separately in both the auditory (e.g., Hari, 1995; Hari &

Kiesilä, 1996; Helenius et al., 1999) and the visual modality (e.g., Hari, Renvall, & Tanskanen, 2001; Hari, Valta, & Uutela, 1999). More specifically, research by Facoetti and colleagues (Facoetti, Lorusso, Cattaneo, Galli, & Molteni, 2005; Facoetti et al., 2010) provides behavioural data to support the suggestion that dyslexic readers have a decreased pace of covert attentional orienting in both auditory and visual modalities; these findings support the proposed magnocellular deficits in which dyslexic readers may struggle with efficient attention allocation across words.

In addition to explaining visual and auditory processing difficulties, the SAS hypothesis can also be used to generate predictions for phonological processing in dyslexic reading. Sluggish attentional shifting disrupts the mapping of orthography with phonology, which, in turn, impedes the development of phonological representations and orthographic-phonological binding (Blomert, 2011; Hari & Renvall, 2001). There is, however, little empirical data that supports the suggested causal relationship between SAS and developmental dyslexia, and no strong evidence linking SAS difficulties to phonological deficits (see Krause, 2015, for a more in depth review of SAS).

In a similar manner to the predictions based on the SAS hypothesis, the SERIOL model (Sequential Encoding Regulated by Inputs to Oscillations within Letter units; Whitney, 2001; Whitney & Cornelissen, 2005) has also been used to propose that visual attention deficits, due to deficient magnocellular functioning, might be a core deficit in developmental dyslexia. Based on their SERIOL model of letter position encoding, Whitney and Cornelissen (2005) purport that dyslexic reading difficulties are associated with visual attention deficits, in which dyslexic readers are unable to adequately allocate attention to individual letters or grapheme clusters. Therefore, readers with dyslexia struggle to activate a single visual letter representation alongside the corresponding letter sound and, as such, a single phoneme may be incorrectly mapped to a number of graphemes. As grapheme-to-phoneme correspondences are poorly developed and unreliable, readers are less likely to access the correct phonological codes through mapping sounds to the written form. This means that, for dyslexic readers, there is less of a requirement to encode the correct left-to-right position of individual letters since the phonological information is not correctly mapped to the graphemes. As such, a lack of grapheme-to-phoneme associations disrupts the formation of an attentional location gradient required to localise the position of letters within a string. Consequently, reading deficits occur due to poor grapheme-to-phoneme mappings as well as problems with encoding letter position information. Whitney and Cornelissen (2005) claim that, in extreme cases, such difficulties may, in fact, cause readers with dyslexia to use an *object style* recognition method in which each word is encoded as a whole visual object rather than developing string specific encoding of letter position information.

In a similar proposal, Vidyasagar and Pammer (2010) argue that attention mechanisms, controlled by the magnocellular stream, aid serial scanning of letters. As such, magnocellular dysfunction is seen to cause disruption in the allocation of serial attention during reading. This is considered to cause the cascade of difficulties discussed above, such as: impairments in the visual processing of graphemes, developing grapheme-phoneme correspondences, and the development of phoneme awareness. Such proposals have been supported by evidence that sensitivity to the spatial order of symbol strings can explain a unique proportion of variability in later reading skill in both children (Pammer, Lavis, Hansen, & Cornelissen, 2004) and adults (Pammer, Lavis, Cooper, Hansen, & Cornelissen, 2005).

In contrast to the accounts discussed above that propose deficits in serial attention allocation explain both phonological difficulties and attentional difficulties in dyslexia, the Visual Attentional (VA) Span Deficit Hypothesis (Bosse et al., 2007; Valdois et al., 2004) postulates a deficit in parallel identification that can be dissociated from phonological deficits in dyslexia. The VA Span Deficit Hypothesis does not align itself with magnocellular dysfunction hypothesis, rather it hinges on the assumption that individuals with dyslexia have a reduced area in which they can allocate attention, which, in turn, limits the number of letters that can be processed in parallel. Bosse et al. (2007) showed that VA span accounts for a substantial amount of unique variance in reading ability in both French and English children with dyslexia. Moreover, through additional analysis, they found that the VA span of English children with dyslexia contributed to reading performance even after controlling for IQ, verbal fluency, vocabulary, single letter identification skills and phoneme awareness; therefore, providing evidence for a causal link between VA span and dyslexia. It is, however, important to note that, the authors of the VA Span Deficit Hypothesis propose dyslexia is caused by multiple cognitive deficits in which both VA span and a phonological disorder play large, yet independent, roles (Bosse et al., 2007). Several studies have shown that deficits in visual attention span are independent of a phonological disorder for a significant number of poor readers (Bosse et al., 2007; Prado, Dubois & Valdois, 2007); however, some individuals may struggle with both visual span and a phonological disorder (Bosse et al., 2007).

VA span deficits have also been reported in Chinese dyslexic readers (Chen, Zheng, & Ho, 2018; Zhao, Liu, Liu, & Huang, 2018). Zhao et al. (2018) demonstrated a reduced VA span for Chinese children with dyslexia in grades 5 and 6 but not in younger children (grades 2, 3, 4). Although they did not find significant difference in the VA span for the younger dyslexic children, they did find a difference in the developmental trajectory of the VA span in Chinese dyslexics compared to typically developing children. Dyslexic children showed a different trajectory in their VA span development which was not representative of a developmental delay but indicated atypical development of the VA span. This is further supported by the work of Chen et al. (2018). Chen et al. found that Chinese dyslexic children performed significantly worse than chronological age matched children on visual attention span, reading, and reading-related cognitive tasks and also performed less well than reading level matched typically developing children in the VA span task. In addition, the results also showed that VA span significantly predicted Chinese word reading accuracy, word and text reading fluency even after controlling for age, IQ, orthographic skills, and rapid naming. This research provides further evidence for the VA Span Deficit Hypothesis (Bosse et al., 2007) and demonstrates a VA span deficit irrespective of language transparency.

Although there is a growing body of research that supports attention deficits within dyslexic populations, there is still a lack of studies that provide evidence for a causal relationship between attention deficits and developmental dyslexia. Furthermore, it is possible that such a deficit may co-occur alongside dyslexia, rather than play any causal role in the aetiology of the reading disability (Pennington, 2009). Interestingly, although a causal link between dyslexia and visual attention has not been formally specified, there are intervention programs based on attention training methods which have demonstrated improved reading in dyslexic readers (see Franceschini et al., 2013). In addition, studies that aim to address the causal link between visual attention deficits and dyslexia typically have a number of limitations. For example, much of the research has been conducted with children who are already learning to read and, consequently, it is hard to form conclusions as to the independent contribution of attention. Certainly, it is possible that children with dyslexia may have developed attentional deficits due to their poorer reading skills and less reading experience. Moreover, many studies have tested children with dyslexia who are at an age where they may have already begun to compensate for any difficulties in low level visual processing (Snowling, 2000). As such, it is difficult to assess the role of attention deficits in causing reading difficulties. Furthermore, attention deficits may manifest in a number of ways; this makes it hard to fully explore and understand the attentional deficits that may impact upon the reading difficulties characteristic of dyslexia. In summary, research into attention deficits in dyslexia provides an interesting line of enquiry; however further empirical research is required in order to draw solid conclusions from the competing theories and to further determine how attention deficits impact upon reading.

1.2.4 Interim summary

Based upon the extensive supporting evidence, it is widely accepted that phonological deficits occur in readers with dyslexia: there is, however, still debate about the general aetiology of dyslexia and to what extent phonological deficits play a causal role in dyslexia. Researchers are proposing theories that aim to further explain the wide range of deficits that occur for readers with dyslexia (not only focusing upon phonological deficits, but also addressing subtle sensory deficits). As such, there has been increasing interest in the role of visual attention in dyslexia and multiple visual attention theories have been suggested (Bosse et al., 2007; Hari & Renvall, 2001; Vidyasagar, 1999; Whitney & Cornelissen, 2005). Although these theories differ in regard to whether the proposed deficits in attention occur within serial attention allocation (whereby dyslexic readers struggle with serial identification of letters and letter position encoding, e.g. Hari & Renvall, 2001; Vidyasagar & Pammer, 2010; Whitney & Cornelissen, 2005) or parallel attention allocation (in which dyslexic readers are limited in the number of letters that can be simultaneously processed, e.g. Bosse et al., 2007), evidence for these proposals is still in its infancy. Furthermore, although some researchers have considered covert spatial attention (Buchholz & Davies, 2005; Corbetta et al., 1998; Rosen et al., 1999), there is a lack of studies fully examining how attention allocation across words may impact dyslexic readers (however, see studies by Hawelka and colleagues that have explored attentional allocation for strings of letters or numbers; Hawelka, Huber, & Wimmer, 2006; Hawelka & Wimmer, 2005).

It is somewhat unsurprising that there are now a range of attentional deficit theories of dyslexia, given the importance of attention and attention allocation during reading (Bellocchi, Muneaux, Bastien-Toniazzo, & Ducrot, 2013; Blythe, 2014). One particular use for attention is parafoveal processing; in order to read effectively, readers have to learn to rapidly shift their attention from one word to the next during sentence reading. Indeed both covert attention and saccadic control rely upon activation within the parietal lobe (Corbetta et al*.,* 1998), therefore visual attentional deficits, due to magnocellular dysfunction, may affect a readers ability to efficiently preprocess visual information in the parafovea. The ability to allocate attention to the next word is key to skilled reading (see Schotter, Angele, & Rayner, 2012 for a review) and, within the eye movement literature, there is a body of work demonstrating the importance of parafoveal processing.

Eye movements provide great insight into the moment-to-moment cognitive processes that occur during reading and, because of this, eye movement research has been highly influential in developing our understanding of skilled adult reading (Liversedge, Gilchrist, & Everling, 2011; Radach & Kennedy, 2013; Rayner, 1998). There is now a large body of research providing evidence for the basic characteristics of eye movements in skilled adult readers (for reviews, see Kirkby, Webster, Blythe, & Liversedge, 2008; Rayner, 1998, 2009), and a number of well-developed models of eye movements for skilled adult readers (e.g. the SWIFT model, Engbert, Longtin, & Kliegl, 2002, and the E-Z Reader model, Pollatsek, Reichle, & Rayner, 2006; Reichle, Pollatsek, Fisher, & Rayner, 1998). Furthermore, as eye movements are closely coupled with attention during reading, eye movements provide us with a great opportunity to examine deficits in dyslexia.

To date there is a paucity of eye movement research into dyslexia and, for this reason, the current thesis aims to extend what is known about eye movements during reading in adults and children with dyslexia, in order to further inform theoretical accounts of dyslexia. The following sections will briefly explain the basic eye movement characteristics, and eye movement control of skilled adult readers before discussing eye movement development and eye movements of readers with dyslexia.

1.3 Eye movements during reading

1.3.1 Basic characteristics of eye movements during reading

Eye movement behaviour is characterised by two defining features: saccades and fixations (Liversedge & Findley, 2000; Rayner, 1998). Saccades are rapid, ballistic eye movements with velocities up to 500 degrees per second. Fixations are the periods between saccades in which the eyes are relatively still. It is during fixations that visual information is extracted from the text; readers do not gain any new visual information during a saccade as saccadic suppression reduces the sensitivity to visual input whilst the eye is moving (Liversedge & Findley, 2000; Matin, 1974). The purpose of saccadic eye movements is to rotate the eye such that light from new and additional information falls onto the fovea during fixation (Rayner, 1998).

The fovea corresponds to the central 2 degrees around fixation and is the area in which our visual acuity is highest. Visual acuity rapidly decreases into the parafoveal region, which extends an additional 5 degrees beyond the fovea. Peripheral vision extends beyond the parafovea and has least visual acuity. Foveal information is extremely important for reading; indeed, it is nearly impossible to read if text is only visible in the parafovea (Rayner & Bertera, 1979; Rayner, Inhoff, Morrison, Slowiaczek, & Bertera, 1981; Rayner, Liversedge, White, & Vergilino-Perez, 2003). Readers do, however, extract useful information from the parafovea in order to facilitate foveal reading (see Schotter et al., 2012 for a review). Recording eye movements allows us to explore foveal and parafoveal processing during reading, both of which are key to skilled adult reading. Successful reading relies upon a reader deciding on when to allocate visual attention from the foveal word to the parafoveal word. Because of the importance of parafoveal, as well as foveal information during reading, paradigms have been designed specifically to test parafoveal processing (McConkie & Rayner, 1975; Rayner, 1975) and these will be discussed later in the chapter.

During silent reading skilled adult readers typically make fixations of 200-250 ms, although there is considerable variability across readers (Rayner, 1978, 1998, 2009), and saccades that occur across 7-9 character spaces with less variability. Skilled adult readers do not fixate all words within a sentence, with readers directly fixating upon approximately 70% of the words in a text. As such, the other 30% of words are skipped. Saccades primarily occur in the direction of reading (left to right in English), however, 10-15% of saccades are regressive saccades that occur in the opposite direction to reading (right to left in English). Regressive saccades, or regressions, are typically made due to disruptions in lexical, syntactic or semantic processing and allow the reader to refixate material that has already been fixated. Regressions are not particularly well understood as it is difficult to control them experimentally (though see Inhoff & Weger, 2005; Murray & Kennedy, 1988; Rayner, Juhasz, Ashby, & Clifton, 2003; Weger & Inhoff, 2006, 2007; for an interesting discussion of regressions due to sentence parsing difficulties, see Mitchell, Shen, Green, & Hodgson, 2008). Many regressions result in fixations upon the immediately preceding word, however, long-range regressions are also made to words that are earlier in the text. These long-range regressions usually occur when comprehension is not going well or the text is particularly difficult. Return sweeps are also right-to-left saccades however these differ to regressions in that return sweeps occur from the end of one line to the beginning of the next; therefore, allowing new text to be read.

It is generally accepted that decisions of when to move the eyes are made independently of decisions of where to move the eyes (Rayner & McConkie, 1976; Rayner & Pollatsek, 1981; Findlay, 1981). Decisions regarding where to move the eyes are largely driven by low-level properties of the text while the decision of when to move the eyes is largely driven by lexical properties of the fixated word (Rayner, 1998). Where we move our eyes is closely related to allocation of visual attention and we shift our attention to a new location before moving our eyes (Deubel & Schneider, 1996; Rayner, McConkie, & Ehrlich, 1978; Shepherd, Findlay, & Hockey, 1986). In order to have efficient foveal and parafoveal processing, and consequently efficient reading, attention, therefore, needs to be adequately allocated during reading.

In reading, the location upon which we fixate is largely determined by the writing system. For alphabetic languages where to move the eyes is strongly influenced by parafoveal information about word length and space information (Sereno & Rayner, 2000). Saccade length is influenced by the combined length of the word *N* and word *N*+1 (Inhoff, Radach, Eiter, & Juhasz, 2003; Juhasz, White, Liversedge, & Rayner, 2008; O'Regan, 1979, 1980; Rayner, 1979; White, Rayner, & Liversedge, 2005a). If word *N*+1 is a particularly long word, then the saccade made from word N will be longer than a saccade made from word *N* if *N*+1 was a medium sized word (Juhasz et al., 2008; Rayner, 1979; White et al., 2005a). A similar pattern follows for saccades made from word *N* if *N*+1 is a particularly short word; because word *N*+1 is a short word, it is likely to be skipped; saccades are, therefore, longer than if word *N*+1 is a medium sized word. Furthermore, spaces between words allow us to determine word length and are used to help target the next saccade. In fact, when spaces are removed from text, reading is negatively affected (Morris, Rayner, & Pollatsek, 1990; Perea & Acha, 2009; Pollatsek & Rayner, 1982; Rayner, Fischer, & Pollatsek, 1998; Rayner & Pollatsek, 1996; Spragins, Lefton, & Fisher, 1976).

Parafoveal information about the spaces between words help readers determine where to target their saccades within a word. Typically, readers land slightly to the left of the centre of the word, known as the preferred viewing location (PVL; Rayner 1979) and when readers' eyes land at a non-optimal position within a word, then they are more likely to refixate that word (O'Regan, 1990; Rayner, Sereno, & Raney, 1996). This is further supported by evidence that when readers receive an incorrect word length parafoveal preview (an incorrect preview during a boundary paradigm experiment), they land in a non-optimal location and, thus, require longer viewing durations once they fixate upon the actual word (Inhoff et al., 2003; Juhasz et al., 2008; White et al., 2005a). Furthermore, parafoveal previews with unusual letter information influence landing positions. A number of studies (Radach, Inhoff, & Heller, 2004; White & Liversedge, 2004, 2006a, 2006b) have found that unusual orthographic word properties affect landing position, and when the initial letters within a word are unusual, landing positions are closer to the beginning (Hyönä, 1995; White & Liversedge, 2006b). This may somehow be due to attention being attracted to the usual letter combinations.

Landing positions also vary as a function of launch sites (McConkie, Kerr, Reddix, & Zola, 1988; Rayner et al., 1996). The position in which you land on a word, then serves as the launch site for the saccade to the next word. If the targeted landing position is far (8-10 letter spaces for example) from the current landing position (i.e. the launch site), then the landing position will shift to the left, whereas, if the distance is small (2-3 letter spaces) then the landing position will be shifted to the right.

Another key issue related to eye movement behaviour is word skipping. Word skipping occurs when words can be processed and identified in parafoveal vision; as such they are not directly fixated (Fisher & Shebilske, 1985; Rayner, White, Kambe, Miller, & Liversedge, 2003). There is evidence that suggests that skipped words are processed during the prior fixation or the fixation after the skip (Kliegl & Engbert, 2005; Pollatsek, Rayner, & Balota, 1986; Rayner et al., 2003; Reichle, Rayner, & Pollatsek, 2003). The likelihood of the word being fixated is somewhat determined by the properties of that word (for example, word length, Rayner & McConkie, 1976; and word type i.e. content or function word, Just & Carpenter, 1980). In fact, there are two key factors, which determine whether a word is skipped: word length and contextual constraint. Short words are skipped more often than long words (Brysbaert, Drieghe, & Vitu, 2005; Drieghe, Brysbaert, Desmet, & De Baecke, 2004; Drieghe, Desmet, & Brysbaert, 2007; Rayner, 1998); 2-3 letter words are fixated approximately 25% of the time compared to 8 letters words which are almost always fixated. Content words are usually fixated (approximately 85% of the time) and function words often skipped (usually fixated about 35% of the time; it must be noted that function words are usually short words). Furthermore, words that are highly constrained based upon the preceding context will have higher skipping rates than words that are not predicable (Balota, Pollatsek, & Rayner.,1985; Binder, Pollatsek, & Rayner, 1999; Ehrlich & Rayner, 1981; Rayner & Well, 1996; Schustack, Ehrlich, & Rayner, 1987; Vitu, 1991). It has also been found that words with higher frequencies increase the likelihood that a word will be skipped; frequency, however, plays a much smaller role in predicting skipping rate than that of predictability (Rayner et al., 1996). Although word predictability influences word skipping and fixation duration, it does not influence the landing position (Rayner, Binder, Ashby, & Pollatsek, 2001; Vainio, Hyönä, & Pajunen, 2009).

Word skipping is largely driven by semantic processing (Blanchard, Pollatsek, & Rayner, 1989; White, Warren, & Reichle, 2011; Yen, Tsai, Tzeng, & Hung, 2008), but this may be somewhat dependent on the properties of the word (Schotter et al., 2012) and some skips may be due to oculomotor error resulting in mislocated fixations, particularly for shorter words (Nuthmann, Engbert, & Kliegl, 2005). In addition to some words being skipped, there are also occasions when words receive multiple fixations before the reader leaves the word (see McConkie, Kerr, Reddix, Zola, & Jacobs, 1989; McDonald & Shillcock, 2004; Vergilino & Beauvillain, 2000, 2001; Vergilino-Perez, Collins, & Dore-Mazars, 2004). These refixations tend to occur when reading long words (such as 8 letter words) and when reading difficult text.

How long the eyes stay fixated upon a word seems to be predominantly determined by how easy or difficult it is to identify the word. Therefore, the decision of when the eyes move is influenced by a range of lexical and linguistic word properties such as word frequency (how often the word is encountered in the language), word predictability (how predictable the word is, given the prior context), age of acquisition (the age at which the word is learned), and so on (for reviews, see Hyönä, 2011; Rayner, 1998, 2009). In fact, two of the most frequently reported effects in the eye movement literature are word length and word frequency; longer words require longer fixation durations than shorter words (Just & Carpenter, 1980; Rayner et al., 1996); and low frequency words require longer fixations than high frequency words (e.g., Henderson & Ferreira, 1990; Inhoff, 1984; Inhoff & Rayner, 1986; Just & Carpenter, 1980; Rayner, 1977; Rayner & Duffy, 1986; Rayner et al., 2003; Rayner & Raney, 1996). We know that cognitive processing influences *when* our eyes move; this has been shown in studies in which the fixated word either disappears or is masked after 50-60ms (Ishida & Ikeda, 1989; Liversedge et al., 2004; Rayner et al., 1981; Rayner, Liversedge, & White, 2006; Rayner et al., 2003). When the fixated word disappears after 50-60ms, the eyes do not instantly move, in fact patterns of eye movement behaviour do not differ to those found during normal presentations where the word does not disappear. Fixation durations are not impacted, and reading continues normally. Rather, the duration of the fixation is determined by the frequency of the fixated word, with fixations lasting longer for low frequency words (Rayner et al., 2003a, 2006), even though the word is no longer visible to the reader. Such findings are a clear indication that cognitive processing drives the duration of fixations during silent reading.

In addition to the basic characteristics of eye movements during reading, research has also determined much about skilled adult parafoveal processing and perceptual span (see Schotter et al., 2012 for a review); the following section will discuss parafoveal processing in more detail.

1.3.2 Parafoveal processing during reading

Parafoveal processing is the ability to pre-process information before directly fixating upon it. During sentence reading, readers extract information from the words they are fixating (i.e., foveal processing) but also from words to the right of fixation (i.e., parafoveal processing; see Rayner, 1998, for a review and Schotter et al., 2012, for a more recent review). The parafovea is the region of the visual field, which extends 2-5 degrees from the centre of vision, however during studies of reading, parafoveal processing is typically tested through the word to the right of fixation (the parafoveal word). The fixated word (word *N*) is processed foveally, whilst the word to the right of fixation (word *N*+1), even though it may not begin exactly 2 degrees from foveal vision, is considered to be processed parafoveally prior to being directly fixated. In fact, a number of paradigms have been developed to test parafoveal processing (McConkie & Rayner, 1975; Rayner, 1975).

The moving window paradigm (McConkie & Rayner, 1975; see Figure 1.2) was developed to determine how far into the parafovea readers can obtain useful information (i.e. the region of effective vision known as the perceptual span) during sentence reading. Within this paradigm the readers' eye movements are monitored and parafoveal vision is purposely restricted so the reader can only see the word in foveal vision and a particular area surrounding it. Accurate information is presented within the moving window (the area in which the information is not restricted), while the information that falls outside the window is masked (usually replaced by other letters or Xs). Using this paradigm, researchers have determined the perceptual span for both adults and children. In English and other alphabetic writing systems, skilled adult readers obtain useful information from an asymmetric region in the direction of reading; the perceptual span extends from 3-4 letters to the left of the fixation (or the beginning of the currently fixated word) to 14-15 letter spaces to the right of fixation (McConkie & Rayner, 1975). The asymmetry of the perceptual span has been suggested to occur as a consequence of covert spatial attention preceding the next eye movement (e.g., Bryden, 1961; Crovitz & Daves, 1962; Greene, Pollatsek, Masserang, Lee, & Rayner, 2010; Henderson, Pollatsek, & Rayner, 1989; Jordan, McGowan, & Paterson, 2014; Klein, 1980; McConkie, 1979; Morrison, 1984; Rayner, Murphy, Henderson, & Pollatsek, 1989; Remington, 1980; Shepherd et al., 1986; Inhoff, Pollatsek, Posner, & Rayner, 1989; Paterson et al., 2014; Pollatsek, Bolozky, Well, & Rayner, 1981; Henderson et al., 1989) rather than due to practice effects. Thus, parafoveal information is primarily acquired from the position that is about to be fixated next.

The moving window paradigm has also been used to explore the letter identity span. The letter identity span is slightly different to the perceptual span as the letter identity span is the number of letters that can be identified during reading and does not usually exceed 8-9 letter spaces to the right of fixation (Häikiö, Bertram, Hyönä, & Niemi, 2009; Morrison & Rayner, 1981; Rayner, 1998).

In addition to using the moving window paradigm, the gaze-contingent boundary paradigm (Rayner, 1975; See Figure 1.3) has been used to determine the extent and nature of the information processed in the parafovea during sentence reading. In the boundary paradigm (Rayner, 1975), an invisible boundary is placed after a pre-target word and to the left of a target word. Whilst the readers' gaze is to the left of the boundary, the target word is manipulated for parafoveal preview. The

Figure 1.2. Example of the moving window paradigm with a two-word window. On each fixation, the fixated word and one word to the right are revealed, while all other letters are replaced with Xs.

preview may be identical to the target word (sometimes called the identity condition) or may have specific manipulations of orthography or phonology for example. Once the reader's eyes cross the invisible boundary, the manipulated preview changes to the correct target word. The display change occurs during a saccade, when vision is adequately suppressed (Matin, 1974), therefore, readers do not usually notice the change (but see Angele, Slattery, & Rayner, 2016; Slattery, Angele, & Rayner, 2011).

Parafoveal information is used to facilitate the processing of word *N*+1 when it is then foveally processed. This facilitation is termed parafoveal preview benefit and has been reported in numerous studies where shorter fixations are made on the target word when the parafoveal preview is identical to the target, compared to when

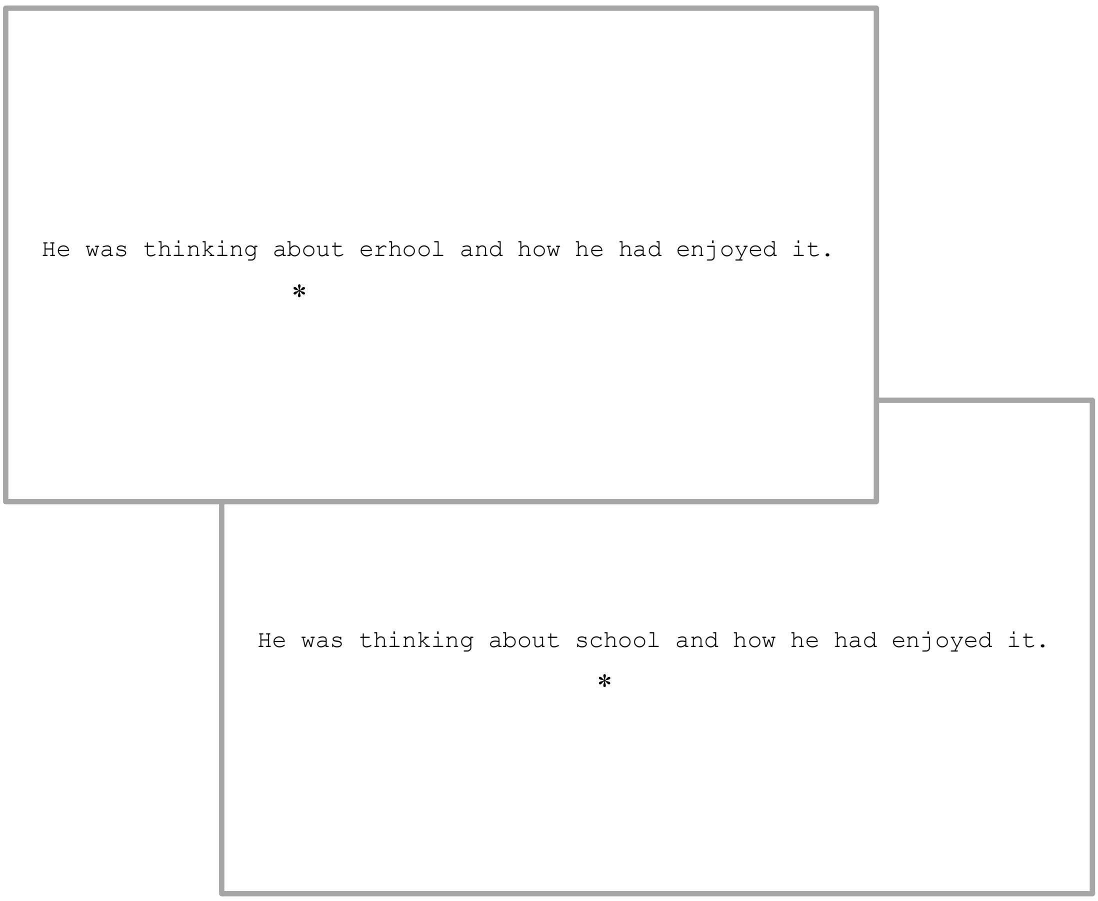

Figure 1.3. Example of the gaze-contingent boundary paradigm. When the subject's eyes cross an invisible boundary before a target word in a sentence, it changes from the manipulated preview to the correct preview.

the preview is non-identical (Schotter et al., 2012). For preview benefit effects in which the identical preview is compared to a non-word or random string of letters, the size of this preview benefit is usually around 30 – 50 ms (Rayner, 2009). Preview effects occur as information, such as beginning and ending letters of words (Briihl & Inhoff, 1995; Inhoff, 1989; Johnson, Perea, & Rayner, 2007; Lima & Inhoff, 1985; Rayner, Well, Pollatsek, & Bertera, 1982) orthographic codes (Balota et al., 1985; Drieghe, Rayner, & Pollatsek, 2005; Rayner, 1975; White et al., 2005a; Williams, Perea, Pollatsek, & Rayner, 2006), semantic information (e.g., Hohenstein & Kliegl, 2014; Rayner & Schotter, 2014; Schotter, 2013; Schotter, Lee, Reiderman, & Rayner, 2015; Tsai, Kliegl, & Yan, 2012; Veldre & Andrews, 2016; White, Bertram, & Hyönä, 2008; Yan, Richter, Shu, & Kliegl, 2009), syntactic information (Drieghe et al., 2017; Veldre & Andrews, 2018), abstract letter codes and phonological information (Ashby & Rayner, 2004; Ashby, Treiman, Kessler, & Rayner, 2006; Blythe, Dickins, Kennedy, & Liversedge, 2018; Chace, Rayner, & Well, 2005; Miellet & Sparrow, 2004; Pollatsek, Lesch, Morris, & Rayner, 1992; Rayner, McConkie, & Zola, 1980; Sparrow & Miellet, 2002) are integrated across saccades. For a review of evidence for orthographic (such as letter identity and letter position), phonological and, to some degree, morphological and semantic preview effects for skilled adult readers see Schotter et al. (2012).

An interesting consideration when exploring parafoveal processing is whether the amount of information we can process within the parafovea is determined by visual acuity or attention constraints. Indeed, perceptual span is asymmetric in the direction of attention allocation, however, Miellet, O'Donnell, and Sereno (2009) developed a variation of the moving window paradigm (parafoveal magnification) to explore whether it is visual acuity or attentional processing that restricts how far into the parafovea readers can gain useful information. Parafoveal magnification magnifies parafoveal text to equalise its perceptual impact with the foveal text, therefore reducing the usual impact of visual acuity. Miellet et al. (2009) demonstrated that parafoveal magnification did not increase the amount of text that was processed. As such, they concluded that parafoveal processing is dependent on attention rather than visual acuity and the amount of information that is processed parafoveally depends on the resources available after foveal processing. This has been supported by research that has found differences in the amount of preview benefit due to manipulations of foveal load; if the fixated word is difficult to process, then readers obtain less preview benefit from the parafoveal word (Henderson & Ferreira, 1990; Kennison & Clifton, 1995; White et al., 2005a; Balota et al., 1985; Drieghe et al., 2005; Vignali, Hawelka, Hutzler, & Richlan, 2019). Therefore, parafoveal processing is restricted by attentional constraints.

From the research discussed thus far, it is clear that skilled adult reading relies greatly upon both foveal and parafoveal processing and the ability to shift attention from the currently fixated to the upcoming word. It is important however to note that skilled adult reading is at the end point of development when both reading skills and oculomotor control are well established. The following section will now explore the eye movement behaviour of children during reading.

1.3.3 Eye movements and reading development

Eye movement research has been extremely useful in developing our understanding of skilled adult reading. Furthermore, in more recent years, researchers have started to use eye movement technology to explore reading development by collecting eye movement data with child participants (for reviews see, Blythe, 2014; Blythe & Joseph, 2011; Rayner, Ardoin, & Binder, 2013). Efforts are now being made to extend models of eye movements to explain reading development (Reichle et al., 2013). Although collecting eye movement data with children is a somewhat challenging process (Blythe & Joseph, 2011), eye movements are a particularly useful measure of reading development as they allow researchers to gain insight into how cognitive processing, visual, and oculomotor systems develop and interact with each other during reading and the process of learning to read (Blythe & Joseph, 2011; Reichle et al., 2013).

In comparison to the research conducted with adults, there is a limited amount of research into children's eye movements during reading. There are, however, some well-designed studies that provide detail about children's eye movements during reading. In an article by Rayner et al. (2013) developmental trends in eye movement behaviour were reported; at the age of 6-7 years old children made 1.9 fixations per word, the average fixation duration was 355 ms and regressions comprised 28% of all fixations. By the age of 8-9 children made 1.3 fixations per word with the average fixation duration being 286 ms and regressions forming 25% of fixations. As children reach 11-12 years old, 1.1 fixations are made per word, on average fixations are 249 ms and regressions had reduced to 22%. In fact, by 11-12 years old children's eye movement patterns are much more similar to adults (who require 0.9 fixations per word, average fixation duration of 233 ms and 14% of all fixations were regressive; see Blythe & Joseph, 2011 for a review). Such evidence was reported by Buswell (1922), Taylor (1966), McConkie et al., (1991), and Rayner (1985a), and these findings suggest that as both chronological age and reading skill increase, the number of fixations (both forward and regressive) and duration of fixations decreases. In addition to the characteristics reported above, a number of studies have also shown that sentence reading times and fixation durations decrease, saccade amplitudes increase, fewer fixations and regressions are made, refixation probability decreases and word skipping probability increases along with increased chronological age and reading skill (Blythe, Häikiö, Bertam, Liversedge, & Hyönä, 2011; Blythe et al., 2006; Blythe, Liversedge, Joseph, White, & Rayner, 2009; Buswell, 1922; Häikiö et al., 2009; Huestegge, Radach,, Corbic, & Huestegge, 2009; Joseph, Liversedge, Blythe, White, & Rayner, 2009; McConkie et al., 1991; Rayner, 1986; Taylor, 1965; Taylor, Frackenpohl, & Pettee, 1960). Such developmental changes in eye movement patterns are considered to predominantly reflect improvements in reading ability, rather than changes in the oculomotor system more generally. Indeed, developmental models of eye movement behaviour suggests children's eye movements result from slower lexical access and lexical processing in children (Reichle et al., 2013).

Similarly to adults, children's decisions on where to move their eyes during reading are driven by low-level properties of the text. Children as young as 7 years old are able to gain sufficient parafoveal information in order to target their saccades toward the word center (McConkie et al., 1991; Vitu, McConkie, Kerr, & O'Regan, 2001). In fact research has shown that, not only do children have similar initial landing position to adults (Aghababian & Nazir, 2000), but children are also more likely to refixate a word if the initial fixation is positioned at the beginning or end of a word (Joseph et al., 2009; McConkie et al., 1991; Vitu et al., 2001). Such findings show that at a young age, child readers are able use low-level parafoveal information to effectively guide their eye movements to improve reading efficiency in a similar manner to skilled adult readers (however, please note that Joseph et al., 2009, did find that children are less efficient when targeting refixation saccades). Furthermore, similarly to adults, children are more likely to skip short words than long words (Hyönä & Olson, 1995; Joseph et al., 2009).

Again, in a similar manner to adult readers, how long children stay fixated upon a word is largely determined by how easy or difficult it is to process the word. Indeed both word length and word frequency effects have been found for children. Joseph et al. (2009) found that word length effects were more pronounced in children compared to adults, suggesting that increased word length has a more substantial effect on children's lexical processing than on that of adults. Such a result is likely due to the demands of visually encoding longer words and therefore children require more and longer visual sampling for long words in order to identify them. In addition to word length effects, word frequency has been found to influence the eye movement patterns of children as young as 7-years of age (Blythe et al., 2006; Hyönä & Olson, 1995). Furthermore, using the disappearing text paradigm, Blythe et al. (2009) found that children as young as 7-years old showed minimal impact of the disappearing text manipulation for manipulations as short as 40ms, and, similarly to adults, effects of word frequency were apparent in measures of single and first fixation duration. Such results provide evidence that even with short presentation times, children as young as 7 years old are able to efficiently encode visual information in order to begin normal lexical identification. This research provides evidence that linguistic processing of the fixated word determines when children move their eyes during reading, thus indicating that children as young as 7 years old display cognitive control of their eye movements during reading. It must, however, be noted that, up until the age of approximately 9 years old, children are slower and less efficient at processing words; they require longer fixations and need additional visual sampling particularly for longer words compared to short words (Blythe et al., 2009; Huestegge et al., 2009; Hyönä & Olson, 1995; Joseph et al., 2009). Therefore, although children's eye movements are controlled by the same mechanisms as adults, children eye movements are affected by their lesser reading skill.

1.3.4 Parafoveal processing in reading development

Parafoveal processing in children is a relatively new line of enquiry; however, the moving window paradigm (McConkie & Rayner, 1975) has been used to identify the perceptual span of both adults and children during reading. Children have a smaller perceptual span than adults; children aged 7 – 9 exhibit a perceptual span which extends 3-4 letter spaces to the left of fixation but only 11 letters to the right of fixation, whereas, 11 year old children have a perceptual span similar to adults, in which the number of letters to the right of fixation extends to 14 letters (Häikiö et al., 2009; Marx, Hutzler, Schuster, & Hawelka, 2016; Rayner, 1986; Sperlich, Schad, & Laubrock, 2015; but also see Both-De Vries, De Jong, Shaul, & Bus, 2016) for a discussion of the perceptual span in pre-readers). Such findings demonstrate that child readers extract less information from the parafovea than skilled adult readers. Indeed, the perceptual span increases with age until 11 years old. It is important to note, however, that these changes have been largely assigned to differences in linguistic processing difficulty (i.e. reading skills; Häikiö et al., 2009; Rayner, 1986) rather than increased visual acuity (Blythe, 2014).

Within their sample of German children (from grades 1, 2 and 3), Sperlich et al. (2015) found that the greatest increase in perceptual span occurs between 2nd grade and 3rd grade. They suggested that the development of parafoveal processing largely relies upon a reader having learnt basic letter and word identification processes such as phonological and lexical decoding. Accordingly, once children reach third grade they are more likely to have established their basic reading skills and are then able to make further use of parafoveal information. This suggestion is further supported by similar longitudinal data (Sperlich, Meixner, & Laubrock, 2016). Furthermore, such results are in support of the proposal that increased foveal demand reduces attentional resources available for parafoveal processing. Sperlich et al. (2015) suggest that the younger readers in grade 1 and 2 rely more upon decoding orthographic information from individual letters into their phonological counterpart, and once this process becomes more automatic (by using graphemes and words for orthographic processing), readers then show more efficient use of parafoveal information as less attention is required for effortful decoding. Again, this proposal is further supported by Marx et al. (2016), who provide evidence for phonological decoding skills as the best predictor of larger parafoveal preview benefits in children learning to read German.

Interestingly, whilst the asymmetry of the perceptual span (where the span is greater to the right of fixation than the left) is present in English readers as young as 7 years old (Rayner, 1986), pre-readers also show a bias to left-to-right processing regardless of reading direction (Both-De Vries et al., 2016). This pre-reading bias is said to be due to the hemispheric set-up of the brain (information presented in the right visual field is perhaps easier to recognise, as it is more directly linked to the left hemisphere which allows for contour-recognition; Both-De Vries et al., 2016; Cabeza & Nyberg, 2000), thus children learning to read in a right-to-left orthography, may be somewhat at a disadvantage when learning to shift their attention in the direction of reading. However, for children learning to read in a left-to-right orthography, only a small amount of reading experience is required, for readers to learn to further allocate their attention in the direction of reading (Rayner, 1986).

Recent research has also started to use the boundary paradigm to determine what information can be parafoveally processed by child readers. To date, there is evidence of orthographic and phonological parafoveal processing in typically developing child readers as young as 8 years old (Häikiö, Bertram & Hyönä, 2010; Marx, Hawelka, Schuster & Hutzler, 2015; Pagán, Blythe, & Liversedge, 2016; Tiffin-Richards & Schroeder, 2015). This indicates that children are able to sufficiently allocate their attention to the parafoveal word in order to extract useful orthographic and/or phonological information thereby facilitating foveal processing of the word once it is then fixated. Currently, it is, however, less clear whether children rely more on phonological or on orthographic encoding within the parafovea (Pagán et al., 2016; Tiffin-Richards & Schroeder, 2015); there have been suggestions that during reading development, children rely more on phonological encoding during parafoveal processing and, in contrast, adults rely on orthographic parafoveal encoding (Tiffin-Richards & Schroeder, 2015).

Whilst the research into parafoveal processing for developing readers is still in its infancy, there is increasing evidence demonstrating that children show similar foveal and parafoveal processing to that of adults at a very young age. In fact, the differences in eye movement patterns, and the patterns occurring within eye movement development, appear to largely reflect children's difficulties in processing the text, rather than the differences in eye movement control. It is their lower reading ability and reduced attentional resources, which drive the longer fixation durations, additional fixations, longer reading times and reduced parafoveal processing. Therefore, this is particularly interesting in relation to the current thesis; dyslexic readers have a lower level reading skill compared to their peers and, in particular, it appears that parafoveal processing may be closely linked to phonological decoding skills of which we know are disrupted in dyslexia. The following section will discuss eye movements during reading for readers with dyslexia.

1.3.5 Eye movements and dyslexic reading

Although there is a growing body of research into children's eye movements during reading, there is still a paucity of eye movement research conducted with readers with developmental dyslexia (although, for a reviews, see Kirkby et al., 2011; Bellocchi et al., 2013). Since we have a basic understanding of developmental eye movement patterns, we can now explore the development of eye movements and reading skill in those with dyslexia. This can help us understand how reading development differs in dyslexic compared to non-dyslexic readers. In addition, dyslexia is often linked to visual or visual attention deficits (Bosse et al., 2007; Hari & Renvall, 2001; Vidyasagar, 1999; Whitney & Cornelissen, 2005), therefore, by recording eye movements in children with dyslexia, we can determine whether differences between typical and dyslexic reading may be due to a cognitive level deficit, reflecting language processing, a visual attentional deficit or an oculomotor deficit.

To date, research has found that, compared non-dyslexic readers, those with dyslexia make more and longer fixations, shorter saccades, and more regressions (Biscaldi, Gezeck, & Stuhr, 1998; De Luca, Borrelli, Judica, Spinelli, & Zoccolotti, 2002; Hatzidaki, Gianneli, Petrakis, Makaronas, & Aslanides, 2011; Hawelka & Wimmer, 2005; Hawelka, Gagl, & Wimmer, 2010; Hutzler & Wimmer, 2004; McConkie et al., 1991; Rayner, 1986). Furthermore, readers with dyslexia skip fewer words and make fewer single fixations; in fact, they often require multiple fixations on the same word (De Luca et al., 2002; De Luca, Di Pace, Judica, Spinelli, Zoccolotti, 1999; Hawelka et al., 2010; Hutzler & Wimmer, 2004; Zoccolotti et al., 1999). However, research has found a similar pattern of eye movements for children with dyslexia compared to typically developing children, matched for reading ability (Hyönä & Olson, 1995; Rayner, 1985a, Rayner 1985b). These children are typically younger in chronological age than the dyslexic readers and therefore they are reading at a level that is expected for their age. Such findings would suggest that differences in eye movement behaviour between children with and without dyslexia are indicative of a cognitive-level linguistic processing deficit, reflecting reading delay, and that, when matched to children of the same reading ability, these differences disappear. There is, however, a lack of studies comparing children with dyslexia to reading-ability matched controls.

Early research by Olson, Conners, and Rack (1991) explored the eye movements of dyslexic readers compared to a group of younger reading-level non-dyslexic children during reading. The non-dyslexic children were matched to the dyslexic readers based upon their word recognition reading scores. Olson et al. found that there were no significant differences between the eye movement patterns of dyslexic readers and those matched for reading skill. They therefore concluded that dyslexic eye movement patterns are a consequence rather than a cause of their reading difficulty.

Hyönä and Olson (1995) then extended the work by Olson et al. (1991) by also further examining the eye movement patterns of dyslexic readers to younger non-dyslexic readers whilst they read aloud. However, in this instance, the two groups were not matched in the same manner as in Olson et al., as they did differ on word recognition ability, with controls having better word recognition skills. Overall, Hyönä and Olson (1995) also found no differences in the eye movement patterns for dyslexic readers compared to younger non-dyslexic readers and again concluded dyslexic eye movements to be indicative of reading delay.

This is further supported by more recent work from Zoccolotti et al. (2005) who found that whilst dyslexic readers showed increased vocal reaction times for single words compared to their peers; they have similar results to children two grades lower. Furthermore, and drawing similar conclusions, De Luca et al. (2002) found that dyslexic children's eye movements, whilst reading lists of words and pseudowords, were demonstrative of their slow, sequential processing of graphemes to phonemes used in the absence of a more rapid global analysis. This once again, supports the notion that dyslexic eye movement patterns are largely explained by their reduced reading skills.

As such, it appears that the typical eye movement patterns reported in dyslexia (longer fixations, more fixations, shorter saccades, more regressions, increased total reading times and so on) are likely to be due to the dyslexic readers' low reading skill rather than an oculomotor deficit in their eye movement control. There is, however, a lack of research into parafoveal processing in dyslexia and specifically the comparison of dyslexic readers to reading-ability matched controls in foveal and parafoveal processing during silent reading. Indeed, there may be differences in the parafoveal processing of the two reading groups because of visual attentional weaknesses in readers with dyslexia. This will be discussed further in this chapter.

Although there are limited studies into eye movements for dyslexic readers during reading, there have been studies exploring landing positions for these readers. Such studies have, in fact, found that adult dyslexic readers tend to land earlier within a word than non-dyslexic adult readers (Hawelka et al., 2010; Pan, Yan, Laubrock, Shu, & Kliegl, 2014), and dyslexic children land earlier in a word than non-dyslexic children (De Luca et al., 2002; MacKeben et al., 2004). Those with dyslexia land at the beginning of the word rather than the usual PVL. As discussed earlier, the ability to target fixations to the PVL usually develops by the age of 7 years for typically developing children (McConkie et al., 1991; Vitu et al., 2001). Therefore, it is possible that this deficit in landing position, found within dyslexic reading, is not due to their poor reading skill but in fact a deficit specific to dyslexia. As such, this deficit may be due to poor oculomotor control in targeting saccades, or due to a lack of parafoveal information to help guide saccade targeting. It must be noted, however, that early landing positions may also be conducive for serial, sublexical word decoding (MacKeben et al., 2004; Marx et al., 2016; Hawelka et al., 2010), in which case these early landing positions may also represent a reliance upon a more effortful reading strategy which also may impact the ability to parafoveally pre-process information.

With regard to eye movement patterns indicative of *when* we move our eyes, dyslexic readers show similar results in comparison to skilled readers. Although there have not been any disappearing text studies conducted with dyslexic readers, there have been studies that demonstrate that both word frequency effects (Ducrot, Pynte, Ghio, & Lété, 2013; Hatzidaki et al., 2011; Hawelka et al., 2010; Hyönä & Olson, 1995) and word length effects (Hawelka et al., 2010; Hyönä & Olson, 1995; Zoccolotti et al., 2005) occur in readers with dyslexia similarly to younger typically developing children. However, note, that these findings largely rely upon eye movement data during reading aloud. Even so, evidence of word frequency and word length effects in dyslexia demonstrate that fixation durations are dependent upon linguistic processing ability for dyslexic readers and, similarly to non-dyslexic readers, eye movements are under cognitive control. Thus differences in viewing duration measures for those with dyslexia compared to non-dyslexic readers tend to reflect the poor reading skills of readers with dyslexia.

1.3.6 Parafoveal processing and dyslexia

Although there have been studies into the development of the perceptual span, only one study has explored the perceptual span during reading for readers with dyslexia (Rayner et al., 1989). Rayner et al. (1989) found a reduced span compared to skilled readers for a small sample of adults with dyslexia. However, Häikiö et al. (2009) did find a reduction in the letter identity span (the number of letters which can be identified during a fixation) for slow child readers compared to fast child readers (please note that this study was conducted in Finland in which dyslexia often manifests as slow reading). Although there has not been much research into the perceptual span particularly for readers with dyslexia, research into the development of the perceptual span suggests that the span increases with reading skill (Blythe, 2014; Häikiö et al., 2009; Rayner, 1986). Therefore, as readers with dyslexia have lower reading skills compared to non-dyslexic children of the same chronological age, one would predict that readers with dyslexia show a reduced perceptual span compared to their peers (this is supported by Rayner et al., 1989). In contrast, it is unclear whether dyslexic readers would in fact show perceptual span deficits when compared to younger non-dyslexic readers who are matched for reading skill. It is possible that dyslexic readers may have a similar perceptual span to non-dyslexic children matched for reading skill, in which case their perceptual span is dictated by their reading ability. It is, however, also possible that dyslexic readers have a reduced perceptual span compared to non-dyslexic children matched for reading skill, suggesting that dyslexic-specific deficits cause their reduced perceptual span.

According to the visual attentional (VA) span deficit hypothesis (Bosse et al., 2007; Valdois et al., 2004), a reduced VA span may cause dyslexia for a proportion of children. Children with dyslexia have, indeed, shown evidence of a reduced VA span (Bosse et al., 2007; Prado et al., 2007; Valdois et al., 2004), in which they can process fewer elements in parallel during a brief visual display than typically developing children. Therefore, if a reduced VA span is a dyslexia-specific deficit, dyslexic readers may show a reduction in the perceptual span and limitations in their ability to parafoveally process information, compared to both typically developing children matched for chronological age but also typically developing children matched for reading age.

Although there is some research exploring the amount of parafoveal information attended to by dyslexic readers, there are currently no studies using the boundary paradigm to examine the type of information encoded during parafoveal processing in dyslexic reading. However, note that Chace et al. (2005) used the boundary paradigm to explore parafoveal processing during reading for a group of skilled and less skilled adult readers. In fact, although Chace et al. (2005) were able to replicate phonological preview benefit effects for the skilled adult reading group, they found no evidence of parafoveal processing in the group of less skilled readers. It is, however, important to note that skilled and less skilled reading groups were defined based upon their scores on the vocabulary and reading comprehension subtests of the Nelson-Denny Reading Test; dyslexia and difficulties with reading comprehension are considered separate disorders (Cain, Oakhill, & Bryant, 2000; Cain, 2010; Hulme & Snowling, 2009; Nation, Adams, Bowyer-Crane, & Snowling, 1999; Nation & Snowling, 1998; Snowling & Hulme, 2012; Stothard & Hulme, 1995). Further explanation of the methodological weaknesses within the Chace et al. design are discussed in detail in both Chapter 3 and Chapter 5. Due to the sample, the results from Chace et al. (2005) may not reflect dyslexic parafoveal processing. It is important to explore parafoveal processing specifically in dyslexic reading for a number of reasons:

1) Parafoveal processing is particularly interesting in respect to dyslexia, as dyslexia may be causally linked to attention deficits (Bosse et al., 2007; Valdois et al., 2004; Hari & Renvall, 2001; Vidyasagar, 1999; Whitney & Cornelissen, 2005) and parafoveal processing is dependent on attention (Miellet et al., 2009).
2) Where saccades land within a sentence is often determined through parafoveal information (Schotter et al., 2012) and readers with dyslexia have been shown to have different saccadic landing positions to skilled adult readers (De Luca et al., 2002; Hawelka et al., 2010; MacKeben et al., 2004; Pan et al., 2014).
3) Dyslexic readers have been found to have a reduced perceptual span (Rayner et al., 1989) and VA span (Bosse et al., 2007; Valdois et al., 2004). They may, therefore, be limited in the amount of parafoveal information they can encode.

4) Independent encoding of letter identity and letter position is characteristic of parafoveal processing in skilled adult readers (Johnson et al., 2007) and dyslexic readers often show attention deficits that result in difficulties in letter position encoding (Casco & Prunetti, 1996; Facoetti, Paganoni, Turatto, Marzola, & Mascetti, 2000; Facoetti et al., 2010; Hari et al., 1999; Solan, Larson, Shelley-Tremblay, Ficarra, & Silverman 2001).
5) Finally, skilled readers can parafoveally encode phonological information (Pollatsek et al., 1992) and, as readers with dyslexia have difficulties in processing phonological information (Liberman, 1973; Snowling, 1995; Snowling, 2000; Stanovich, 1988), we would expect that readers with dyslexia do not experience the usual phonological preview benefits that occur for skilled readers.

The proposal that dyslexic readers have deficits in processing parafoveal information is not a new suggestion (e.g., Bouma & Legein, 1977), but there are still limitations in what we know about dyslexic parafoveal processing. The earlier work into dyslexic parafoveal dysfunction was largely focused upon crowding. Crowding (also known as lateral masking) is a perceptual phenomenon defined as the interference of flanking letters on the recognition of the target letter (Bouma, 1970, 1973). This interference has detrimental effects upon letter encoding, which is a fundamental stage in reading (Pelli, Farell & Moore, 2003; Perry et al., 2007). Crowding is found in both skilled and dyslexic readers but there are numerous studies that have demonstrated increased crowding for dyslexic readers during both foveal (Bouma & Legein, 1977; Callens, Whitney, Tops, & Brysbaert, 2013; Martelli, Di Filippo, Spinelli, & Zoccolotti, 2009; Moll & Jones, 2013; Moores, Cassim, & Talcott, 2011; Spinelli, De Luca, Judica, & Zoccolotti, 2002) and parafoveal processing (Bouma & Legein, 1977; Martelli et al., 2009; Moll & Jones, 2013; Pernet, Valdois, Celsis, & Démonet, 2006). In fact, interventions that focus on reducing crowding by increasing inter-letter spacing show evidence for improved reading performance, particularly for those with dyslexia (Perea, Panadero, Moret-Tatay, & Gómez, 2012; Spinelli et al., 2002; Zorzi et al., 2012).

Increased crowding may, therefore, impair letter recognition during parafoveal processing for readers with dyslexia. However, it is unclear whether crowding is a deficit specific to dyslexic readers during parafoveal processing, as effects of crowding have been demonstrated in both foveal and parafoveal processing. Moreover, although crowding has been largely considered to occur as a function of visual attention deficits (Bellocchi et al., 2013), there is evidence to suggest that the presence of flanking letters may not influence visual processing specifically, but actually occur as a result of readers attempting to extract phonological information from the crowded items (Hawelka & Wimmer, 2008; Jones et al., 2008). Thus, it may be the case that increased crowding effects occur more generally during reading for readers with dyslexia due to their difficulties within processing phonological information rather than a specific deficit in relation to parafoveal processing during reading.

Further to the crowding literature, there is a growing body of evidence that explores dyslexic parafoveal processing during Rapid Automised Naming (RAN, Wolf & Denckla, 2005). RAN requires readers to rapidly name visually presented arrays of letters, numbers, colours or objects that are presented randomly within rows. RAN tests naming speed, a measure of how quickly one can integrate visual and language processes. Poor RAN scores are often considered to reflect poor phonological processing (Clarke, Hulme, & Snowling, 2005), however, RAN has been found to independently predict dyslexia in readers who do not necessarily show phonological deficits (Wolf & Bowers, 1999; Wolf, Bowers, & Biddle, 2000; Torppa et al., 2013). RAN has been found to reflect several stages of lexical processing (for example, orthographic and phonological selection and visual–verbal integration; Jones et al., 2008, 2010, 2013), thus RAN similarly requires many of the component processes that are necessary during reading. It must be noted, however, that although RAN performance does reflect reading performance (in particular reading fluency), RAN is an artificial task and, as such, there are a number of differences in RAN and reading tasks. For example, reading usually requires comprehension therefore adding a level of additional complexity to the task, and, RAN presentations are usually comprised of arrays of individual letters or individual numbers as such the item is much less visually and cognitively complex compared to words within a sentence. That said, there have been some extremely useful insights into dyslexic parafoveal processing based upon studies from RAN.

Studies using RAN tasks have found parafoveal preview benefits for readers with dyslexia (Jones et al., 2008, 2010, 2013; Yan, Pan, Laubrock, Kliegl, & Shu, 2013). More specifically, Yan et al. (2013) provided evidence for less efficient orthographic parafoveal processing in Chinese dyslexic child readers compared to typically developing child readers. Yan et al. (2013) implemented the moving window paradigm during a RAN task to test whether children with dyslexia show a narrower perceptual span. They presented children with dyslexia and chronological age match controls with two RAN tasks: a continuous RAN task (in which all letters were presented at the same time) and a discrete RAN task (where one letter was presented at a time, therefore, removing the possibility of parafoveally processing the next letter). Eye movements were recorded whilst children read aloud the letters. Within their findings, Yan et al. (2013) showed that removing a parafoveal preview of the upcoming letter disrupted both groups of readers, i.e. naming times and viewing durations were longer during the discrete RAN than the continuous RAN. This indicates that children with dyslexia do make use of information in their parafovea, and, processing of a letter occurs prior to fixation during a RAN task. However, Yan et al. (2013) showed an interaction between reading ability and RAN condition in which children with dyslexia were less disrupted by the discrete RAN task than the typically developing children. Therefore, Yan et al. (2013) concluded that children with dyslexia were less efficient in their use of parafoveal information and suggested this is probably due to dyslexic readers requiring greater attentional resources for foveal processing.

In addition to Yan et al. (2013), Jones and colleagues have published a body of work exploring parafoveal processing during RAN which demonstrates that whilst dyslexic readers do make use of parafoveal information during RAN, parafoveal information is in fact a potential source of confusion (Jones et al., 2008, 2010, 2013). More specifically, Jones et al. (2013) found that dyslexic readers were more susceptible to orthographic confusability in the parafovea and phonological confusability in the fovea. Jones et al. (2013) found that the processing of two consecutive letters is disrupted when the parafoveal information from the second letter is orthographically similar, thus confusable, to the first letter. However, this effect occurred whilst fixating upon the second letter rather than the first letter; therefore, dyslexic readers fixated the second letter for longer if it was orthographically similar to the previous letter (the first letter) when it appeared parafoveally (even though the second letter was not orthographically similar to the first letter during fixation). As such, Jones et al. (2013) suggest that not only is there interference from parafoveal information for dyslexic readers, but also there is a lag in the effect from the interference that indicates slower parafoveal processing for readers with dyslexia. Therefore, dyslexic readers show parafoveal deficits in regard to orthographic confusability as well as processing delay, both of which may negatively impact their reading.

For the results of the foveal processing, Jones et al. (2013) found that dyslexic readers, compared to non-dyslexic readers, were slower to articulate letter names when phonologically similar information was present in the fovea. This occurred in two ways; 1) when trying to articulate the phonological information of the previously fixated letter (*N*), the currently fixated letters (*N*+1) phonological information interfered. 2) Dyslexic readers also struggled to disengage with already activated phonological information when it was similar to the phonological information of the next item; dyslexic readers were slower to name *N*+1 because the activated phonological information from N was interfering. In sum, Jones et al. (2013) found that dyslexic readers experience a "processing bottleneck" where they demonstrate greater difficulty in selecting information from competing alternatives and such effects occur across both parafoveal and foveal processing. The authors conclude that the confusability found in readers with dyslexia may result from degraded orthographic and phonological representations, making it more difficult for those with dyslexia to distinguish between, and thus slower to select and retrieve, the correct orthographic and phonological representations.

In order to try to extend the work by Jones and colleagues, Silva et al. (2016) aimed to understand whether dyslexic readers show difficulties that are due to either a lack of parafoveal information, or, from parafoveal information disrupting the encoding of the foveal information. In order to explore this, Silva et al. (2016) recorded eye movements of dyslexic and non-dyslexic adults during a modified serial RAN task. In their naming task, they manipulated the parafoveal load (whether or not there was an item presented within the parafovea) and the parafoveal preview potential of each item (whether the item was previewed parafoveally or not). Dyslexic readers showed evidence of reduced parafoveal processing compared to skilled readers but no differences in the effect of parafoveal load. Therefore, dyslexic readers appear to encode less parafoveal information than non-dyslexic readers, but, are not increasingly impacted by having parafoveal information available whilst they are encoding the foveal item. Thus, Silva et al. (2016) suggested that dyslexic limitations in parafoveal processing might be due to attentional restrictions (that occur as a consequence of difficulties in extracting phonological information from the foveal information) rather than interference from the parafoveal information during foveal processing.

In sum, the research exploring dyslexic parafoveal processing during RAN suggests that dyslexic readers are somewhat less efficient in their parafoveal processing abilities than non-dyslexic readers (Jones et al., 2008, 2010, 2013; Silva et al., 2016; Yan et al., 2013). Whilst the findings from RAN provide a useful basis for exploring dyslexic parafoveal processing, there are, however, very few studies exploring parafoveal processing during silent sentence reading for readers with dyslexia (however see Rayner et al. (1989) who demonstrated that a small sample of readers with dyslexia have a reduced perceptual span). As such, it is still unclear as to how parafoveal processing difficulties may impact reading for readers with dyslexia. In fact, dyslexic readers may show a range of parafoveal processing difficulties during reading. Dyslexic readers may have reduced parafoveal preview benefits compared to non-dyslexic readers, where dyslexic readers gain less facilitation from the parafoveal information. Due to sluggish attention, they may show delayed parafoveal processing in which the time course of parafoveal preview effects may occur later in time for readers with dyslexia compared to non-dyslexic readers (which may also result in reduced parafoveal preview benefits). Furthermore, dyslexic readers may have specific difficulties encoding certain types of information within the parafovea (e.g. letter position of phonological information). Thus, the current thesis aimed to examine parafoveal processing during reading for readers with dyslexia in order to further our understanding of attentional deficits in readers with dyslexia. The specific thesis aims are outlined below.

1.4 Chapter summary and aims of the thesis

This chapter provides a detailed review of the literature on developmental dyslexia, theories of dyslexia, and, eye movements during foveal and parafoveal processing for dyslexic and non-dyslexic readers. Within the above literature review, it is clear that there are a number of issues and areas that need additional research in order to further our understanding of dyslexia. Whilst there are a number of attention deficit theories of dyslexia (Bosse et al., 2007; Hari & Renvall, 2001; Vidyasagar, 1999; Whitney & Cornelissen, 2005), it is currently unclear exactly how attention deficits impact silent reading for dyslexic readers. Although eye movement research is particularly useful in developing our understanding of attentional processes during reading, there is a lack of eye movement studies detailing eye movement behaviour for readers with dyslexia during silent reading. In fact, there is a particular lack of research in regard to parafoveal processing during reading for readers with dyslexia; this is surprising given number of theories suggesting that attention deficits play a causal role in dyslexia (Bosse et al., 2007; Hari & Renvall, 2001; Vidyasagar, 1999; Whitney & Cornelissen, 2005), and the importance of attention allocation specifically for parafoveal processing (Miellet et al., 2009; Schotter et al., 2012). Therefore, this thesis aimed to provide additional research in order to further develop our understanding of dyslexia by recording eye movements during reading. Specifically, this thesis aimed to:

1) to provide a detailed characterisation of dyslexic foveal eye movement patterns during silent reading, for both adults and children,
2) to determine whether dyslexic adults and children gain parafoveal previews benefits during silent sentence reading,
3) to understand what information is encoded from the parafovea during dyslexic silent sentence reading,
4) to explore the nature of the dyslexic eye movement patterns by experimentally comparing children with dyslexia to groups of typically developing children matched for chronological age, but also typically developing children matched for reading age.

Thus, this thesis reports three research studies conducted to address these aims. The following chapter details the specifics of the methodological approach adopted to address these aims.

Chapter Two: Methodological considerations

2.0 Chapter overview

Whilst some aspects of the methodology have been discussed briefly during Chapter 1, this chapter will identify the key methodological considerations that were made, in order to address the aims of the thesis. As the main focus of this thesis was to develop an understanding of dyslexia through examining eye movement behaviour, the chapter starts by outlining the specific eye movement measures and relevant eye movement terminology used throughout the thesis. This is followed by a discussion of the participant groups and the offline testing used to verify the participant group allocation. Finally, this chapter includes discussions of the specific paradigm selected to examine parafoveal processing, and the statistical analyses conducted for this thesis.

2.1 Eye movement measures and terminology

This section provides an overview of the eye movement measures selected within this thesis and examination of the terminology used to categorise different eye movement measures. In the first instance, the distinction between global and local eye movements will be explained. Global measures refer to aggregated eye movement data from a whole sentence and allow us to look more broadly upon differences in eye movement behaviour that are not specific to a particular word or manipulation. In fact, differences in eye movement behaviour may accumulate over a sentence, whilst individual fixations may not differ greatly in duration; these small differences can accumulate and, therefore, impact measures such as total reading time. As such, global eye movements provide a useful measure to explore group differences in dyslexic and non-dyslexic readers during silent sentence reading. Furthermore, within boundary paradigm studies, global eye movement data is, typically, not impacted by the target word manipulation of parafoveal preview and, thus, provides a useful indication of differences in eye movement behaviour for dyslexic and non-dyslexic readers independently of the specific target word manipulation.

In contrast to global measures, local measures are the eye movements that occur specifically in a region of interest (in this case, on the target word manipulated for parafoveal preview). Local eye movement measures are much more specific, allowing for a detailed examination of how a particular linguistic manipulation may impact cognitive linguistic processing and, thus, influence eye movement behaviour. Within the current thesis, the impact of manipulated parafoveal previews was examined using local measures, as they are able to demonstrate the subtle effects of parafoveal preview benefits. In addition to being extremely useful at indicating the effects of specific target word manipulations, local measures are often used to demonstrate the differences in eye movement behaviour for dyslexic readers compared to non-dyslexic readers. Whilst global measures provide an indication of accumulated or averaged eye movement behaviour across a sentence (i.e. average fixation duration, total reading time), local measures provide a better indication of differences in individual fixations (i.e. first fixation duration, single fixation duration). Unlike global measures, however, local measures do not provide an indication of group differences independently of the specific experimental manipulation. Therefore, and particularly when examining differences in reading groups, it is important to include both global measures, to gain a broader understanding of the differences in groups across sentence reading and local measures, to provide more fine-grain detail on eye movement measures of reading, as well as to explore the impact of parafoveal manipulations. For this reason, the experiments detailed throughout this thesis include analysis of both global and local eye movement measures. The following section describes the eye movement measures used throughout the experiments reported in this thesis.

For the global analysis the following eye movements were computed: total sentence reading time, average saccade amplitude, average forward and regressive fixation duration, and total number of forward and regressive fixations per sentence. Total reading time is the sum of all fixations that occur throughout the whole trial (including any regressive fixations). Forward and regressive fixations were classified based upon the previous saccade direction (fixations preceded by a rightward saccade are considered forward fixations and fixations preceded by a leftward saccade are referred to as regressive fixations). In addition, the following eye movement measures were computed for local analysis: first fixation duration, single fixation duration, gaze duration, go-past time, total reading time and also landing position. First fixation duration is the duration of the initial fixation on the target word. Single fixation duration represents those fixations for which the reader made only one fixation on the target word during first pass (first pass is the initial instance when an eye movement is made into the target region until it leaves the target region, any subsequent eye movements to that region are not first pass eye movements). Gaze duration is the sum of fixation durations on the target word, before the reader leaves that word. Go-past time is the sum of fixation durations from when a reader first fixated the target word until their first fixation to the right of that word (including any regressions made before moving forward past the target word). For local measures, total reading time is the sum of all fixations that occur on the *target word* throughout the whole trial (including any regressive fixations). Landing position is the character location on which the eye fixates. This variety of local eye movement measures were largely selected due to their distinction in being early and late measures.

The distinction between early and late measures is interesting, because the point at which a specific manipulation has an impact upon the eye movement behaviour may be informative about the nature of the underlying cognitive processes occurring at that point within reading (Clifton, Staub, & Rayner, 2007). To clarify, in reading, early eye movement measures are the initial eye movements that occur within a word or region, before leaving that word or region for the first time, such as single fixation duration, first fixation duration and gaze duration (however gaze duration may also incorporate some in-word first pass regressions). These early eye movement measures regularly produce similar patterns of effects (but not always; Rayner & Liversedge, 2011) and are good indices of initial lexical processing (Rayner & Liversedge, 2011). Late eye movement measures are those that involve revisiting a word or region, in which case the word or region has already been fixated. Examples of late eye movement measures are those such as go-past time and total reading time and tend to reflect later stages of processing, such as semantic and discourse processing.

Within the current thesis, both early and late eye movement measures were recorded. Including both early and late measures provides a useful indication of the time-course of processing for the different reading groups, allowing for comparison on both early lexical processing and later semantic and discourse processing. Furthermore, studies have reported different eye movement behaviours for readers with dyslexia compared to non-dyslexic readers, during both early and late eye movement measures (Hawelka et al., 2010; Hutzler, Kronbichler, Jacobs, &

Wimmer, 2006; Hutzler, & Wimmer, 2004; Hyönä, & Olson, 1995; MacKeben et al., 2004). Moreover, it is possible that dyslexic readers may show delayed processing relative to skilled adult readers (e.g., Hari, & Kiesilä, 1996; Helenius et al., 1999; Merzenich et al., 1993), in which case it is important to include a range of eye movement measures.

In addition to early measures being useful in exploring the difference between reading groups (e.g. dyslexic or non-dyslexic), early measures are also particularly important when exploring parafoveal processing using the boundary paradigm. Early measures are often used within boundary paradigm studies because the manipulations of parafoveal processing occur before the reader fixates the word. Consequently, the effects of the manipulation typically occur within the initial eye movements made onto that word. Thus, similarly to a range of boundary paradigm studies (e.g., Chace et al., 2005; Häikiö et al., 2010; Johnson et al., 2007; Marx et al., 2015; Pagán et al., 2016; Pollatsek et al., 1992; Tiffin-Richards & Schroeder, 2015), early measures such as first fixation duration and single fixation duration were included to examine the impact of parafoveal preview manipulations. The research reported throughout this thesis, therefore, included both early and late measures of reading, in an attempt to better understand the time-course of the reading process for readers with dyslexia and to ensure the impact of the parafoveal processing manipulations were explored.

In sum, eye movements differ in regard to whether they are global or local measures, and also early or late measures. In order to address the aims of the thesis, it is important to include range of eye movement measures. In fact, by using both global and local and early and late eye movement measures, it is possible to gain a detailed understanding of the time course of word identification, for both foveal and parafoveal processing during dyslexic and non-dyslexic reading.

2.2 Adult and child participant groups

In addition to selecting the appropriate eye movement measures for the experiments, it was crucial to select suitable participant groups. Specifically, as the primary aim of this thesis was to further our understanding of developmental dyslexia, it was important to explore reading deficits across the developmental trajectory. In fact, the developmental process can impact the reading difficulties found within readers with dyslexia (Karmiloff-Smith, 1998). For this reason, the research for this thesis was conducted with both adult readers (who are at the latter end of reading development) and children (who are still developing their reading skills). Whilst there are a number of strengths and weaknesses associated with testing either of these specific samples alone, testing both child and adult samples can be much more useful. Indeed, testing with both children and adults helps to provide a greater understanding of the deficits that occur throughout development. The following section details the specific reasoning for exploring effects across both children and adults. This section aims to explain why adult readers were selected for both Experiment 1 and Experiment 3 (reported in Chapter 3 and Chapter 5 respectively). Furthermore, this section provides detail as to why the experimental design from Experiment 1 was then used as the basis for Experiment 2, conducted with children (reported in Chapter 4).

Adult samples of dyslexic readers were selected for two of the experimental chapters (both Experiment 1 detailed in Chapter 3 and Experiment 2 in Chapter 4). One key reason for selecting an adult sample for these two experimental chapters was to determine whether dyslexic readers do, in fact, gain parafoveal preview benefits during reading. As discussed within the initial chapter of this thesis, there were very few studies exploring parafoveal processing for readers with dyslexia (however, see Jones et al., 2008, 2010, 2013; Silva et al., 2016; Yan et al., 2013, who conducted research into dyslexic parafoveal processing during RAN). Consequently, both Experiment 1 and Experiment 3 provided a novel exploration of parafoveal processing during reading for readers with dyslexia; Experiment 1 focused upon orthographic parafoveal processing and Experiment 3 on phonological parafoveal processing. It was unclear whether readers with dyslexia would gain preview benefits and how these preview benefits may manifest during reading. For this reason, data was initially collected with adults, in order to first establish that dyslexic readers, at the latter end of the reading development trajectory, were able to develop the skills required to parafoveally process information during reading. These findings were then useful to provide a foundation to examining the development of parafoveal processing in children with dyslexia.

Another benefit of initially testing adult dyslexic readers is that there is a body of work exploring parafoveal processing for skilled adults (for a review see Schotter et al., 2012). This research provides a useful foundation to understanding and predicting parafoveal processing for dyslexic adults. For children, however, there is far less research into parafoveal processing (Pagán et al., 2016; Tiffin-

Richards & Schroeder, 2015) and some inconsistencies with regard to the age at which parafoveal processing skills develop. It would have been challenging to conduct these initial studies with a dyslexic child sample, as it was unclear whether dyslexic children would gain parafoveal preview benefits and, if so, at what age they would develop. Furthermore, by specifically examining parafoveal processing in dyslexic adult readers, who are at the latter end of reading development, it is then more logical to develop predictions for additional studies exploring the development of parafoveal processing with dyslexic children. Accordingly, both Experiment 1 and Experiment 3 used adults' dyslexic samples to explore parafoveal processing in adult dyslexia.

Whilst is it extremely useful to use adult samples to initially determine whether dyslexic readers can gain parafoveal preview benefits during reading, there are a number of weaknesses in testing adult samples. There has been critique about using adult samples to explore a developmental disorder, as they do not represent the *development* that occurs within a disorder and this makes it difficult to draw conclusions upon the etiology of dyslexia (Karmiloff-Smith; 1998). Although the current research did not directly address the causes of dyslexia, it is still important to consider the role of development in a developmental disorder. Karmiloff-Smith (1998) proposed the Neuroconstructivist approach to developmental disorders, which recommends that, in order to fully understand developmental disorders, one needs to consider the dynamics of development and how a child's developmental trajectory will be impacted due to the specific deficits that occur early within their life (Elman et al., 1996; Karmiloff-Smith, 1998).

The Neuroconstructivist approach considers that development is an interactive process during which the cognitive system is able to self-organise in response to particular deficits. Due to such flexibility and self-organisation, this approach also considers that people with a developmental disorder may exhibit specific strengths as well as weaknesses and that particular areas of cognitive strength may help to compensate for areas of weakness (Perin, 1983; Stanovich, 1980; Walley, 1993). Therefore, dyslexic adults, especially those enrolled within higher education, are often considered to be 'compensated' dyslexic readers who have developed compensatory strategies that enable them to read at an adequate level. Consequently, Karmiloff-Smith (1998) suggests that it is important to separate behavioural outcomes from underlying cognitive processes. In fact, it is possible that the behaviours that are observed in adults with dyslexia are not associated with the cause of dyslexia, but rather an outcome of their earlier deficits in learning to read. The eye movement patterns and parafoveal processing abilities of adults with dyslexia may differ to those found for dyslexic children, as they may reflect compensatory strategies. It was, therefore, extremely important that the research reported within this thesis not only included adult readers, in order to establish that parafoveal processing does occur in dyslexia, but also to test children with dyslexia in order to further understand the development of parafoveal processing. Consequently, the results from Experiment 1 were the extended to explore parafoveal processing for children (Experiment 2, Chapter 4).

Finally, recall the aim throughout this thesis was not only to explore the extent to which parafoveal processing occurs in dyslexic reading, but also explore the nature of the dyslexic reading deficit. To this end, dyslexic children were tested alongside both typically developing children, matched for chronological age (these children were the same age as the dyslexic children but had an increased reading age) and typically developing children matched for reading age (these children were chronologically younger than the dyslexic readers but had the same reading age). Thus in Experiment 2, eye movements were recorded from 3 child samples; children with dyslexia, typically developing children matched for chronological age and typically developing children matched for reading age. By comparing dyslexic children to both of these control samples, one can determine whether deficits in dyslexic parafoveal processing are, in fact, specific to dyslexia, or due to a developmental lag. If the deficit is specific to dyslexia, dyslexic readers would show different eye movement patterns compared to both control groups. If, however, dyslexic reading behaviour is indicative of a developmental lag, then dyslexic readers would show similar behavioural patterns when compared to typically developing children matched for reading age.

Within the eye movement and reading literature, research has demonstrated that eye movement patterns typically reflect difficulties in linguistic processing (Häikiö et al., 2009; Kirkby et al., 2008; Rayner, 1986), thus it is possible that dyslexic eye movement patterns are purely representative of their reduced reading skill in comparison to typically developing children matched for chronological age. As discussed in the introductory chapter, there is very little research exploring eye movement behaviour of dyslexic readers in comparison to both chronological age matched children and reading age matched children. Accordingly within the current thesis, it was important, not only to extend the findings of parafoveal preview benefit in adults to children, but also to further our understanding of the nature of reading difficulties in dyslexia, through testing both chronological age matched and reading age matched control groups.

2.3 Offline testing

Another methodological consideration discussed within this chapter is that of offline testing. Although all dyslexic readers tested within this thesis had a prior independent diagnosis of dyslexia, in order to establish that our groups of readers showed patterns representative of their reading group (i.e. dyslexic and non-dyslexic readers, age or reading age matched control groups), offline tests were conducted. These offline tests were used to gain further understanding of their general intelligence and reading profiles. This section provides a discussion of specific offline tests used and why they were chosen.

The first consideration in regard to offline testing was general intelligence. General intelligence is an individual's ability to acquire and apply knowledge and skills and is, typically, measured through tests of intelligence quotient (IQ). In previous years, general intelligence was widely used to help diagnose dyslexia through the discrepancy approach (Ellis, McDougall, & Monk, 1996; Rutter & Yule, 1975). The discrepancy approach to diagnosis required that children with dyslexia had a reading age that was lower than their general intelligence scores would predict. In fact, a number of researchers exploring developmental dyslexia previously considered the IQ-discrepant group to be the core dyslexic population (e.g. Ellis et al., 1996) and considered dyslexic readers to be distinct from other poor readers, due to their specific reading deficit in relation to their cognitive ability. There has, however, been a growing body of evidence to discredit the role of IQ in dyslexia. Specifically, there is limited support for the suggestion that the discrepancy between IQ and reading is an important predictor of the difference in decoding for dyslexic readers compared to poor readers who are not considered to be dyslexic (Fletcher et al., 2007; Hoskyn & Swanson, 2000; Stuebing, Barth, Molfese, Weiss, & Fletcher, 2009; Stuebing et al., 2002). Similarly, there has been little evidence that IQ discrepancy can differentiate between readers who benefit from intervention and those who do not (Gresham & Vellutino, 2010). Furthermore, IQ discrepancy appears to provide very little prognostic information about future reading ability (Flowers, Meyer, Lovato, Wood, & Felton, 2001; Francis, Shaywitz, Stuebing, Shaywitz, & Fletcher, 1996). In general, the IQ-discrepancy approach is no longer supported as a diagnostic measure (e.g. Hatcher & Hulme, 1999; Shaywitz, Fletcher, Holahan, & Shaywitz, 1992; Stanovich, 2005; Stanovich & Siegel, 1994; Vellutino et al., 2004). In fact, it is now typically accepted that individuals with all levels of general intelligence can be diagnosed with dyslexia (Snowling & Hulme, 2012). That said, IQ is, however, still used as part of the exclusion criteria to assess dyslexic readers, for research purposes (Rice & Brooks, 2004).

Studies of dyslexia often examine IQ in order to control for below average intelligence scores (Rice & Brooks, 2004). Individuals with low general intelligence may have underlying cognitive deficits that are not causally linked to dyslexia but do in fact impact on reading ability. Thus, in order to test dyslexic reading difficulties, it is useful to exclude participants whose general intelligence is below average and may, therefore, impact their ability to read (Snowling, 2008). As such, measuring IQ allows for exploration of the underlying cognitive deficits associated with dyslexic reading (Snowling, 2008), without additional cognitive deficits that occur due to low IQ, but may also impact reading behaviour. Consequently, throughout the three experimental chapters (Chapter 3, 4, and 5) IQ was measured using the two subtests version of the Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler, 1999), to ensure that participants had an average or above average IQ score (IQ≥90; Wechsler, 1999).

The two-subtest version of the WASI includes a vocabulary subtest and a matrix reasoning subtest. The vocabulary subtest is a 42-item task, which requires participants to provide an oral definition of each item, and measures the participant's expressive vocabulary, verbal knowledge and general information learning. Indeed the vocabulary subtest task is used to examine cognitive abilities such as, memory, learning ability, concept and language development (Sattler, 1988). The matrix reasoning subtest, comprised of 35 items, requires participants to identify (from a number of choices) the missing item within a gridded pattern. This test measures non-verbal fluid reasoning and general intellectual ability. Together, these scores provide an IQ score for each participant, which can be used to determine whether the individual meets the score of average/above average IQ. Dyslexic and non-dyslexic readers did not significantly differ in measures on IQ (see individual chapters for further details).

In addition to examining the IQ of participants, further testing was conducted to examine reading skills. As dyslexia is often diagnosed through deficits in decoding (Snowling & Hulme, 2012), it is usually assessed by measures of word recognition, phonological awareness and phonological decoding. These are typically assessed through reading aloud a range of single words and a range of pseudowords. Consequently, within each experimental chapter of this thesis, participants were required to take part in word reading and pseudoword reading tasks. In the single word reading task, readers had to read aloud a set of increasingly challenging words. Specifically, single word reading is an assessment of letter knowledge, phonological awareness and decoding and sight-word knowledge. Although the task may require some explicit phonological decoding (especially for the more challenging words), readers cannot solely rely upon phonological decoding as a method to correctly read the words. In fact, there are a number of irregular words on the list, which cannot be phonologically decoded to provide the correct pronunciation, and thus participants have to rely upon their sight-word knowledge. As reading skills develop, readers typically move from a precise serial approach to reading, to a more automated, whole word method of reading. The serial approach to reading is time consuming and requires the reader to phonologically decode individual letters in order to sound out the word. In contrast, when a reader becomes more experienced, they are able to use a much more automated, fluent approach that relies on sight-word knowledge; allowing the reader to extract the phonological representations from the orthographic representation of the word rather than its individual letters (Ehri, 2010). To achieve high scores on these single word reading tests, it is expected that readers are able to both phonologically decode words and also use sight-word knowledge in order to read. Sight-word knowledge is dependent upon the ability to map graphemes to phonemes and create well-developed orthographic representations. Therefore, as readers with dyslexia have difficulties with decoding, they also tend to struggle with sight-word knowledge (Ehri, 1997). Thus, readers with dyslexia tend to show poor scores on test of single word reading.

In contrast to tests of single word reading, tests of pseudoword decoding require readers have to read aloud a list of orthographically legal and therefore pronounceable non-words. Due to the nature of the task, readers cannot rely upon their sight-word knowledge and have to explicitly decode the sounds within the words in order to correctly pronounce the pseudoword. As such, this task is a more direct assessment of phonological decoding and is usually challenging for readers with dyslexia. In fact, readers with dyslexia typically perform poorly on both measures of single word reading and pseudoword reading. It is for this reason that both single word reading and pseudoword decoding tests were administered to all participants throughout the work reported in this thesis. For adults, the Test of Word Reading Efficiency was used (TOWRE; Torgesen, Wagner, & Rashotte, 1999); for children the Word Reading and Pseudoword Reading subtests of the Wechsler Individual Achievement Test – Second Edition (WIAT-II; Wechsler, 2005) was administered. The specific set tests used for each population are discussed in further detail during the individual experimental chapters. In addition to completing word and pseudoword reading tests, participants were also required to take part in RAN (rapid automised naming) tests of letters and numbers.

RAN requires readers to rapidly name visually presented arrays of letters, or, numbers that are presented randomly within rows. Tests of RAN examine how well individuals can integrate both visual and language information and have been found to correlate with (see Bowey, 2005; Kirby, Georgiou, Martinussen, & Parrila, 2010, for reviews) and predict reading ability (Lervåg & Hulme, 2009). RAN scores have been found to be predictive of reading ability independently of skills in letter knowledge and phoneme awareness, and some dyslexic readers have been found to show average phoneme awareness but poor RAN (Wolf & Denckla, 2005). Therefore, in addition to tests of word and pseudoword reading, RAN scores were collected for readers with and without dyslexia. Specifically, the letter and number subsets of RAN were administered to all participants, as these subtests have been found to be consistent predictors of reading across reading development (Kirby, Parrila, &, Pfeiffer, 2003; Shaywitz & Shaywitz, 2005; Wolf & Obregón, 1992).

2.4 The boundary paradigm

Further to understanding both eye movement measures and terminology and selecting the appropriate samples to explore dyslexic deficits, consideration was given to ensure the most appropriate paradigm was selected to examine parafoveal processing during reading for readers with dyslexia. As discussed in the introductory chapter, there are two well established methodological approaches that have been used to explore eye movements and parafoveal processing, particularly during studies of reading: the moving window paradigm (McConkie & Rayner, 1975) and the boundary paradigm (Rayner, 1975).

The moving window paradigm (McConkie & Rayner, 1975; see Figure 1.2 in Chapter 1) was developed to determine how far into the parafovea readers can obtain useful information (i.e. the region of effective vision known as the perceptual span) during sentence reading. Specifically, using the moving window paradigm during reading, Rayner et al. (1989) found that dyslexic readers had a reduced perceptual span compared to non-dyslexic readers. Whilst there has only been one study directly measuring the perceptual span for dyslexic readers during reading (Rayner et al., 1989), this finding is supported by research showing that increases in the perceptual span are largely attributed to improved reading skills (Häikiö et al., 2009; Rayner, 1986).

Although there is some research into the perceptual span of readers with dyslexia (Rayner et al., 1989), very little is known about the type of information readers with dyslexia can encode from the parafovea. The boundary paradigm (explained fully in Chapter 1, Rayner, 1975; See Figure 1.3) is used to determine the extent and nature of the information processed in the parafovea during sentence reading and research has demonstrated that a range of information, such as orthographic (e.g. letter identity and letter position), phonological, morphological, and semantic information, can provide parafoveal preview benefits to skilled adults during reading (e.g. Ashby & Rayner, 2004; Ashby et al., 2006; Balota et al., 1985; Blythe et al., 2018; Chace et al., 2005; Deutsch, Frost, Pelleg, Pollatsek, & Rayner, 2003; Deutsch, Frost, Pollatsek, & Rayner, 2000, 2005; Drieghe et al., 2005; Hohenstein, Laubrock, & Kliegl, 2010; Miellet & Sparrow, 2004; Pollatsek et al., 1992; Pollatsek, Tan, & Rayner, 2000; Rayner, 1975; Rayner et al., 1980; Sparrow & Miellet, 2002; White, Rayner, & Liversedge, 2005b; Williams et al., 2006; Yan et al., 2009). There were, however, no studies that had used the boundary paradigm to explore dyslexic reading (although some great insights have been provided by studies using RAN; Jones et al., 2013; Silva et al., 2016; Yan et al., 2013). It was, consequently, unclear as to what information dyslexic readers could encode parafoveally during sentence reading. Dyslexia may be causally related to attentional deficits that impact letter position encoding (Vidyasagar & Pammer, 2010; Whitney & Cornelissen, 2005), therefore, readers with dyslexia may have struggled with the parafoveal encoding of orthographic information. Moreover, dyslexia is defined by deficits in phonological processing (Liberman, 1973; Snowling, 1995; Snowling, 2000; Stanovich, 1988); readers with dyslexia may in fact have shown difficulties in encoding phonological information from the parafovea during reading. Thus, as this thesis focused upon determining what information (specifically, orthographic and phonological) dyslexic readers can extract from parafovea during reading, the boundary paradigm was selected as the most appropriate method.

2.5 Data analysis

The final discussion presented here concerns the method of statistical analysis used for eye movement studies of reading. In 1973, Clark provided a critique of the statistical procedures used in studies of language; specifically, he proposed that, in addition to considering participants as random variables (in which it is acknowledged that the research outcomes need to be generalised beyond the individual participants to the wider population), researchers should also treat language materials as random variables. Indeed, not only do individual participants vary at a range of levels (due to factors such as genetic, developmental, environmental, social, or political influences), but experimental stimuli such as sentences also vary on a range of levels (such as variations in words, syllables, and language). Thus, both participants and language materials should be considered as random variables within the analysis. This recommendation by Clark (1973) resulted in many studies then reporting statistical analyses (typically in the form of analysis of variance, ANOVAs) for both the participants (F1) involved within the study and the items (F2, the specific set of words or sentences) used within the study (Raaijmakers, Schrijnemakers, & Gremmen, 1999). This was based on a widely held assumption that research findings could be generalised to both the participant population and the language as a whole, if the participant and items analysis were conducted separately (Raaijmakers et al., 1999). Whilst such practice was not actually in line with the recommendations of Clark (1973), this became the typical format for eye movement analysis for studies of reading. The original issues raised by Clark et al. (1973) were not addressed and, in many cases, it was still unclear whether research findings could in fact be generalised to both the participant population and the language.

A new statistical approach, linear mixed modeling (LMM), has recently become popular within the eye movement and reading literature (Baayen, Davidson,

& Bates, 2008; Barr, Levy, Scheepers, & Tily, 2013), as it is able to address these issues raised by Clark (1973). Linear mixed models (LMMs) can include both random and fixed effects within one model, with both effects being modeled as having a linear form. Fixed effects are the variables that have been purposely manipulated and thus have an *a priori* theoretical motivation for statistical analysis (Pinheiro & Bates, 2000); for example, the fixed effects reported in the current thesis were the manipulations of parafoveal preview and also the reading group. In contrast, random effects are variables that typically occur when individual data points cluster together, via association with a set of entities, but are not variables that have been manipulated. For example, the random effects reported in the current thesis were participants and items (sets of stimuli), as the data points can be grouped by individual participants and individual items.

It is the inclusion of these additional random effects alongside the fixed effects that makes the linear mixed model a *mixed* model and a popular method within research into language. Adding the random effects into the linear model provides structure within the model error and allows for the variation in the data to be characterised. Thus, in studies of language, as reported in this thesis, both participants and items can be included as random factors within the same model, which then characterises the variation in the data that is due to individual differences in both participants and the selected stimuli. Therefore, analysis conducted using LMMs does address the concerns raised by Clark (1973), by allowing both participants and items to be considered as random variables within the same model. This means that, research using LMMs allows for the research to be generalised across both participants and items and is one of the reasons that LMM's are now becoming the preferred method of analysis for researchers exploring eye movement behaviour during reading (e.g. Marx et al., 2016; Marx, Hawelka, Schuster, & Hutzler, 2017; Pagán et al., 2016; Tiffin-Richards, & Schroeder, 2015).

In addition to the ability to include both fixed and random effects within one model, LMMs are also known to accommodate for instances of missing data (Gurka & Edwards, 2011; Kutner, Nachtsheim, Neter, & Li, 2005; Smith, 2012; West, Welch, & Galecki, 2007), which is not the case for more traditional methods of analysis such as the ANOVA. Indeed, missing data and unbalanced designs occur regularly when testing special populations, as data collection can be often challenging and the number of participants often limited (Blythe & Joseph, 2011).

Furthermore, missing data occurs regularly during eye movement studies of reading, particularly in boundary paradigm studies where a strict exclusion criterion is followed and portions of the data have to be excluded to ensure accurate data. In line with a range of boundary paradigm studies (Angele & Rayner, 2011; Angele, Slattery, Yang, Kliegl, & Rayner, 2008; Chace et al., 2005; Häikiö et al., 2010; Johnson et al., 2007; Kliegl, Risse, & Laubrock, 2007; Marx et al., 2015; Pagán et al., 2016; Pollatsek et al.,1992; Tiffin-Richards & Schroeder, 2015), a strict exclusion criteria was followed to ensure that the gaze contingent change worked efficiently and effectively in presenting a parafoveal preview independently to the foveal preview (see the experimental chapters for detail on the individual criteria). Therefore, due to the nature of this thesis (exploring eye movement behaviour for readers with dyslexia using the boundary paradigm), it was considered highly likely that there would be instances of missing data and that using LMMs to analyse the data would be beneficial. For these reasons, similarly to a range of studies in eye movements and reading (e.g. Bélanger, Mayberry, & Rayner, 2013; Hawelka et al., 2010; Kirkby et al., 2011; Marx et al., 2017; Pagán et al., 2016; Sperlich et al., 2015; Tiffin-Richards, & Schroeder, 2015; Yan et al., 2013), LMMs were selected as the main method of analysis for the eye movement data.

2.6 Chapter summary

In sum, this chapter provided a discussion of the key methodological considerations that were made prior to experimental testing and data analysis. These decisions allowed for thorough and well-controlled experimental design and analysis in order to explore parafoveal processing for dyslexic readers. The next chapter presents the first experiment, which used the boundary paradigm to explore orthographic parafoveal processing in skilled and dyslexic adult readers.

Chapter Three: Experiment 1

3.0 Chapter overview

Within the first two chapters of this thesis, the gaps within dyslexic literature have been identified, the thesis aims been outlined and the rationale for the methodology provided. This chapter is the first experimental chapter of this thesis. This experiment aimed to provide initial evidence for dyslexic adult parafoveal processing of orthographic information. Specifically, using the boundary paradigm, the experiment explored whether dyslexic adults can parafoveally encode letter identity and letter position during silent sentence reading.

Orthographic parafoveal processing in adults with dyslexia

3.1 Introduction

As discussed within Chapter 1, developmental dyslexia is a severe, persistent, and specific disorder of reading development that affects between 5-20% of children, despite normal intelligence and adequate reading instruction (Shaywitz, 1998). This chronic reading disorder is characterised by impaired decoding skills - the ability to map phonology (speech sounds) to orthography (the written form; Snowling & Hulme, 2012). Indeed, this characterisation is further supported by the fact that the most widely accepted theory of dyslexia is the Phonological Deficit Hypothesis (Liberman, 1973; Snowling, 1995; Snowling, 2000; Stanovich, 1988), in which dyslexia is caused by a cognitive level deficit in accessing and representing phonological information. However, it is important to note that the deficits in accessing and representing phonological information may occur due to difficulties in either the phonological or orthographic counterpart of decoding (Castles & Coltheart, 2004). Furthermore, phonological decoding is an attention-demanding process (Reynolds & Besner, 2006) that requires both phonological skills (Ramus, 2003; Ziegler & Goswami, 2005) and efficient allocation of visual attention (Cestnick & Coltheart, 1999; Facoetti et al., 2006; Perry et al., 2007). In addition, there is a body of evidence suggesting that dyslexia is also associated with visual attention allocation deficits that may cause difficulties in the serial scanning of letters and encoding of letter position; this then impacts upon the development of phonological skills by disrupting the mapping of orthographic and phonological information (Vidyasagar & Pammer, 2010; Whitney & Cornelissen, 2005).

Skilled reading relies upon reader's correctly and rapidly identifying phonological information from orthographic form. Thus, readers need to be able to sufficiently allocate their attention, in order to identify the orthographic properties of a word, such as letter identity and letter position, and then determine the correct phonological mapping for that letter or combination of letters. Indeed, letter identity and letter position encoding are fundamental processes in visual word recognition that allows a reader to distinguish between the phonological outputs of anagrams such as *was* and *saw*. Whilst letter position is an important aspect of visual word recognition, it is encoded with a level of flexibility, particularly for skilled adult readers. Studies of single word recognition in skilled adult readers have shown that non-words with a transposition of two letters (e.g. *jugde*) are more similar to the base word (e.g. *judge*) than non-words with two substituted letters (e.g. *jupte*; Chambers, 1979; Christianson, Johnson, & Rayner, 2005; Forster, Davis, Schoknecht, & Carter, 1987; O'Connor & Forster, 1981; Perea & Fraga, 2006; Perea & Lupker, 2003a, 2003b, 2004). This is known as the transposed letter (TL) effect and indicates that words with transposed letters significantly activate the lexical representation of the base word more than words with substituted letters. Therefore, letter identity encoding is not specific to letter position; letter identity and letter position are encoded independently of one another and skilled readers have a level of flexibility within their letter position encoding.

In support of the body of work demonstrating flexible letter position encoding, there are now a number of visual word recognition models that aim to explain how letters are encoded with such flexibility (Davis, 1999, 2010; Gómez, Ratcliff & Perea, 2008; Grainger & van Heuven, 2003; Whitney, 2001). In particular, the SERIOL model (Whitney, 2001) proposes that letter position is encoded through open bigrams and that this encoding of open bigrams depends on the development of an attentional location gradient. It is this attentional location gradient, that develops in a bottom-up manner through experience, that allows readers to serially encode letter order, activate the corresponding open bigrams and then encode letter position with a level of flexibility.

Based upon their SERIOL model, Whitney and Cornelissen (2005) propose that attention deficits in dyslexia may impact the formation of the attentional location gradient. Dyslexic readers struggle with encoding letter position information, which then causes difficulties in establishing the correct grapheme to phoneme correspondences. Whitney and Cornelissen (2005) claim that, in extreme cases, such difficulties may cause readers with dyslexia to use an *object style* recognition method in which each word is encoded as a whole visual object rather than a letter string. In a similar proposal, Vidyasagar and Pammer (2010) argue that attention deficits cause disruption in the allocation of serial attention during reading and this is considered to cause a cascade of difficulties such as difficulties in letter position encoding and impairments in developing grapheme-phoneme correspondences. Indeed, such proposals have been supported by evidence that sensitivity to the spatial order of symbol strings can explain a unique proportion of variability in later reading skill in both children (Pammer et al., 2004) and adults (Pammer et al., 2005).

Although letter position is flexibly encoded for skilled adult readers, the location of the letter position transposition also has an impact on how well the transposition non-word activates the lexical representation of the base word (Johnson et al., 2007; Perea & Lupker, 2003a, 2003b, 2004, 2007; Schoonbaert & Grainger, 2004; Tiffin-Richards & Schroeder, 2015; White, Johnson, Liversedge, & Rayner, 2008). A series of lexical decision experiments exploring TL effects for single word recognition have demonstrated that transpositions that occur internally (for example *jugde*) are more likely to activate the lexical representation of the base word than letter transpositions that occur externally (for example *ujdge*) (Perea & Lupker, 2003a, 2003b). Such findings have also been replicated during silent sentence reading; transposing the internal letters of a word causes less disruption to reading compared to when the external letters are transposed (Rayner, White, Johnson, & Liversedge, 2006). Transposing the initial letter causes the greatest disruption to reading, suggesting initial letter transpositions have the greatest influence on lexical activation (Johnson & Dunne, 2012; Johnson & Eisler, 2012; Johnson et al., 2007; Tiffin-Richards & Schroeder, 2015; White et al., 2008).

In order to examine why word-initial letters have greater importance than internal letters, White et al. (2008) explored two possible explanations. The first explanation focused on the visual processing of the word, specifically, the fact that English words are presented spatially left to right and English readers read left to right. Therefore, when fixating upon a word, the initial letters of the next word are closer to the fovea and as, visually, acuity decreases from the fovea to the parafovea to the periphery, the initial letters of the next word are more clearly visible in the parafovea than the internal and end letters of that word. Thus, transpositions in word-initial letters may cause greater disruption during reading due to their spatial location. The second possible explanation focuses on lexical identification and suggests that the initial letters of a word are, perhaps, intrinsically more important for lexical identification. It may be that letters within a word are processed from left to right during lexical identification and, as a consequence, these initial letters are more important in allowing readers to determine the word.

In order to examine these competing explanations, White et al. (2008) used the moving window paradigm (McConkie & Rayner, 1975) to restrict the availability of parafoveal preview information for skilled adult readers whilst they read sentences with transposed letters. They found that, even with a restricted parafoveal preview, transpositions within the initial letters of words still caused greater disruption to lexical processing than internal transpositions. This suggests, therefore, that the importance of the initial letters of a word does not occur as a consequence of the spatial location of the letters (i.e. the parafoveal preview being visually clearer); but rather due to some intrinsic importance of the initial letters in regard to lexical identification. It is possible that this intrinsic importance of the initial letters may be related to the need for sequential activation of phonological codes, particularly in determining the phonological onset of a word, in order to activate phonological representations of words during reading.

Research to date has demonstrated that phonological information is encoded before lexical access (for a review see Leinenger, 2014) and, whilst orthographic codes appear to be activated slightly earlier than phonological codes (Lee, Rayner, & Pollatsek, 1999), it is likely that phonological information may still impact lexical activation (Leinenger, 2014; Miellet & Sparrow, 2004). This can help to explain the increased importance of encoding letter position for word-initial letters, as demonstrated by White et al. (2008); disrupting the initial letters may have an impact on both orthographic processing, but also phonological processing, through disrupting the sequential activation of phonological codes. In fact, the phonological codes may help to restrict the number of suitable lexical candidates (Folk & Morris, 1995), or aid in activating the correct lexical representation (Lima & Inhoff, 1985).

However, we propose that it is the phonological codes for the initial letters that are most useful due to sequential processing of phonological information. In this case, the letter order would need to be encoded, allowing phonological codes to be activated sequentially, thus permitting a reader to both identify and also pronounce the word in the correct manner. A dyslexic reader's difficulties in encoding phonological information may be explained, at least to some degree, by difficulties in the sequential processing of letter information (Whitney & Cornelissen, 2005).

While models of letter position encoding (Davis, 1999, 2010; Gómez et al., 2008; Grainger & van Heuven, 2003; Whitney, 2001) are useful in explaining flexible letter position encoding for letters processed foveally, they have not yet been extended to consider how readers encode orthographic information in the parafovea. There is, however, a body of work that has found evidence for the TL effect and the importance of initial letter position information in parafoveal processing during silent sentence reading for skilled adult readers and children (Johnson et al., 2007; Pagán et al., 2016; Tiffin-Richards & Schroeder, 2015).

Recall, parafoveal processing is the ability to extract useful information from the parafovea in order to facilitate reading; whilst fixating word *N*, readers allocate their attention to word *N*+1 and start pre-processing the word prior to fixation. Therefore, attention allocation is extremely important to parafoveal processing and research has demonstrated that the amount of information processed parafoveally is dependent on the attentional resources available after foveal processing (Miellet et al., 2009). As discussed in detail in Chapter 1, a common method of exploring parafoveal processing and parafoveal preview benefits during reading is the boundary paradigm (Rayner, 1975; see Schotter et al., 2012 for a review). In the boundary paradigm an invisible boundary is placed between a pre-target and target word and, when the reader's gaze is left of the boundary, the target word is manipulated for parafoveal preview. Once the reader's eyes move across the boundary, the preview word changes to the original target word. A parafoveal preview benefit is apparent from shorter fixations on the target word when the parafoveal preview is identical to the target, compared to when the parafoveal preview is manipulated.

Using the boundary paradigm, Johnson et al. (2007) explored the TL effect during parafoveal processing. They demonstrated that identical previews (e.g., *judge*) received shorter fixation durations compared to both transposed-letter previews (e.g., *jugde*) and substituted-letter previews (e.g., *judpe*). As identical previews provided greater facilitation than substituted-letter previews, the results provided evidence of parafoveal preview benefits in skilled adult readers. In addition, identical previews provided greater facilitation than transposed-letter previews indicating that letter position information is encoded from the parafovea; if parafoveal preview benefits were driven by letter identity alone then identical previews and transposed-letter previews would provide equal facilitation. Furthermore, and in line with the single word recognition studies, transposed-letter previews received shorter fixation times compared to substituted-letter previews, thus demonstrating the TL effect. This pattern of results suggests that letter identity information is encoded independently to letter position, and therefore flexibly, in the parafovea for skilled adult readers.

Further to establishing that the TL effect occurs during parafoveal processing, Johnson et al. (2007) also demonstrated that orthographic manipulations of external letters, both the initial letter and final letter, cause greater disruption to visual word recognition than manipulations that occur internally within the word during parafoveal processing. Therefore, the TL effect is weaker for external letters compared to internal letters and for external letters there appears to be greater dependence of letter identity encoding upon letter position encoding. In line with studies of foveal processing, Johnson et al. (2007) proposed that these external letters play an important role in visual word recognition, even during the parafoveal processing of words. Indeed, this work by Johnson et al. (2007) has been further supported by Pagán et al. (2016) and Tiffin-Richards and Schroeder (2015). Pagán et al. (2016) provided further evidence for the TL effect occurring in the initial trigram of the parafoveal word for both adults and child readers. Specifically, the TL effect was found for transpositions and substitutions that occurred in the first two letters of the parafoveal word (letter positions 1 and 2) and for the second two letters of the parafoveal word (letter positions 2 and 3). In addition, Tiffin-Richards and Schroeder (2015), in their examination of both phonological and orthographic parafoveal processing, found that adult readers exhibited a TL effect for internal letter transpositions but a reduced TL effect of initial transpositions. Thus further demonstrating that skilled readers flexibly encode letter position during reading and that the initial letters have increased importance (compared to internal letters) during parafoveal processing.

While there have been numerous studies into parafoveal processing for skilled adult readers (see Schotter et al., 2012), and recent progress in research on the development of parafoveal processing (Häikiö et al., 2009, 2010; Pagán et al., 2016; Marx et al., 2015; Tiffin-Richards & Schroeder, 2015), there is a paucity of research exploring parafoveal processing in dyslexic reading (however see Jones et al., 2013, and Yan et al., 2013, who found evidence for parafoveal processing for dyslexic readers during Rapid Automised Naming; RAN, Wolf & Denckla, 2005). Although not specifically testing dyslexic readers, one study (Chace et al., 2005) explored parafoveal processing during reading for a sample of university readers who were divided into groups of less skilled and skilled reading adults. Indeed, Chace et al. (2005) used the boundary paradigm with the following preview conditions: identical to the target word (i.e. *beach*), a homophone of the target word (*beech*), an orthographic control (*bench*), or a random letter string (*jfzrp*). Consistent with prior research, skilled adult readers obtained the usual preview benefit in which identical previews provided greater facilitation than random letter strings. Furthermore, skilled readers also showed a benefit of homophone previews compared to orthographic previews, demonstrating the parafoveal processing of both orthographic and phonological information for skilled readers. The less skilled readers, however, did not show a benefit of homophone previews compared to orthographic previews and very little benefit of identical previews compared to random letter strings. As such, Chace et al. (2005) concluded that less skilled readers showed no evidence of any type of preview benefit, and that increased foveal load (Henderson & Ferreira, 1990; Rayner, 1986; Vignali et al., 2019), induced through the use of low frequency pre-target words (33 counts per million; BNC, British National Corpus), might have prevented parafoveal processing for the less skilled readers.

Whilst this is interesting in regard to parafoveal processing for readers with dyslexia, it must be noted that the skilled and less skilled reading groups used within Chace et al. (2005) were determined based on their scores on the vocabulary and reading comprehension subtests of the Nelson-Denny Reading Test (Brown, Bennett, & Hanna, 1981). Thus, the less skilled reading group used by Chace et al. (2005) would have been readers with poor vocabulary and comprehension, not necessarily readers with impaired decoding skills (i.e. readers with dyslexia). In fact, it is important to note that dyslexia and difficulties with reading comprehension are often considered separate disorders; Cain et al., 2000; Cain, 2010; Hulme & Snowling, 2009; Nation et al., 1999; Nation & Snowling, 1998b; Snowling & Hulme, 2012; Stothard & Hulme, 1995). In which case, the parafoveal processing difficulties found in the less skilled reading group tested in Chace et al. (2005), may not represent the parafoveal processing difficulties that occur for readers with dyslexia. Indeed, whilst Chace et al. (2005) found no evidence of parafoveal processing for their less skilled reading group, studies have demonstrated that both adult and child dyslexic readers do in fact gain parafoveal preview benefits during RAN tasks (Jones et al., 2013; Yan et al., 2013). As such, is it still unclear as to whether readers with dyslexia do in fact gain orthographic parafoveal preview benefits during reading.

The current study examined the transposed letter effect for the initial letters of a word during parafoveal processing in adults with and without dyslexia. Although transposed letter effects may be reduced within the initial letters for skilled readers, the initial letters were manipulated for the following reasons. The first reason was to optimise the opportunity for dyslexic readers to demonstrate a parafoveal preview benefit. Indeed, Rayner et al., (1989) found a reduced perceptual span (defined as the region of effective vision) within their small sample of dyslexic readers. As such, positioning the manipulation within the first 2 letters of the target word increases the possibility to find effects of parafoveal processing even if dyslexic readers have a restricted perceptual span. Furthermore, as discussed earlier within this chapter, transposing the initial letters of a word may indeed heighten the disruption caused to readers with dyslexia, given the importance of initial letters (perhaps due to sequential mapping of phonological information) and dyslexic readers' difficulty with mapping phonology to orthography. Therefore, using identical previews (IP; e.g. *nearly*), transposed-letter previews (TL; e.g. *enarly*), and substituted-letter previews (SL; e.g. *acarly*) the current study aimed to clarify; 1) whether adults with dyslexia exhibit parafoveal preview benefit during reading by examining to what extent dyslexic readers can encode orthographic information parafoveally, as, to our knowledge, no studies have yet tested dyslexic parafoveal processing during sentence reading, and 2) explore the extent to which transposing letters disrupts reading for dyslexic readers in comparison with skilled adult readers.

Further to Jones et al. (2013) and Yan et al. (2013), who provide evidence for parafoveal processing in dyslexic reading during a RAN task, we predicted that adults with dyslexia would show parafoveal preview benefit as demonstrated through reduced viewing durations for identical previews compared to substituted-letter previews. Furthermore, based upon the proposed visual attention deficits (Vidyasagar & Pammer, 2010; Whitney & Cornelissen, 2005), the following predictions were made. If dyslexic readers encode letter position extremely flexibly (or perhaps not at all), then dyslexic readers would gain similar preview benefit for both identical previews and transposed-letter previews (as they both provide the correct letter identity information regardless of letter position). Such result would indicate that readers with dyslexia do not show an importance of initial letter information. Conversely, if adults with dyslexia have a greater dependence on letter position information, perhaps due to encoding words as visual objects (Whitney & Cornelissen, 2005): they would gain a preview benefit for identical previews compared to both transposed-letter previews and substituted-letter previews, with no additional benefit of pre-processing the transposed-letter preview compared to the substituted-letter preview. This would indicate that dyslexic readers rely heavily on the correct letter position information and, consequently, have not developed a skilled attentional location gradient that allows for flexibility during the encoding of letter position. Alternatively, dyslexic readers may not show any deficits in attention allocation during parafoveal processing: in which case, dyslexic readers should show the usual orthographic preview benefits (benefit of identical previews compared to transposed-letter previews and transposed-letter previews compared to substituted-letter previews) in the same manner as the skilled adult readers.

3.2 Method

3.2.1 Participants

Participants were 25 university students with developmental dyslexia (mean age of 21 years and 6 months, SD: 4 years and 6 months) and 26 university students without dyslexia (mean age 20 years 3 months, SD: 1 years and 3 months). Students with dyslexia had a prior, independent diagnosis of dyslexia and such diagnosis was further supported by deficits in standardised tests of reading ability (see Results section). All participants were native English speakers with normal or corrected to normal vision and were recruited from Bournemouth University. All participants performed within the normal range on a standardised intelligence test (IQ≥90).

3.2.2 Apparatus

Eye movements were recorded from the right eye using a SR Research Eyelink 1000 eye-tracker. Sentences were presented at a viewing distance of 660 mm on a 21 inch Formac ProNitron 21/750 monitor with a screen resolution of 1024 x 768 pixels and a refresh rate of 120 Hz. Sentences were presented in black 14pt Courier New font on a white background.

3.2.3 Design and stimuli

Three parafoveal preview conditions were presented using the boundary paradigm (Rayner, 1975). Parafoveal previews of the target words were either 1) identical to the target word, 2) a transposed-letter non-word, or 3) a substituted-letter non-word. The manipulation occurred in the initial two letters of the target word to both examine the impact of parafoveal processing for initial letters (which may in fact have a specific importance related to phonological processing) but also because these letters are indeed spatially closer to foveal vision and dyslexic readers may have reduced perceptual span (Rayner et al., 1989). For the transposed-letter conditions, the positions of the two initial letters were switched and for the substituted-letter conditions the initial two letters were replaced with visually similar letters (ascenders were replaced with ascenders and descenders with descenders) to retain orthographic similarity. Target words were always 6 letter words and preceded by a 5 or 6 letter pre-target word to increase the likelihood of a readers fixating upon both the words. Pre-target and target words were presented to the middle of the sentence and were high frequency words. In contrast to Chace et al. (2005), who used low frequency pre-target words, the current design specifically selected high frequency pre-target and target words in attempt to reduce foveal load and allow for parafoveal processing. The mean frequency of the pre-target word was 535 counts per million and the mean frequency of the target word was 262 counts per million (BNC; British National Corpus).

The stimuli consisted of 90 sentence frames and for each sentence frame there were 3 versions corresponding to the three parafoveal preview conditions (See Table 3.1 for an example). Three experimental lists were constructed whereby each list contained a different version of each sentence frame and the parafoveal preview manipulations were randomised across the 3 experimental lists, so that each participant saw 30 sentences from each of the three preview conditions.

The eye movement contingent change boundary was located at the end of the pre-target word and to the left of the space preceding the target word. When the eyes moved past the invisible boundary, the target word changed from the parafoveal preview to the target word. The correct target word then remained in the sentence throughout the remaining duration of the trial. Display changes were typically undetected by the readers as they occurred during a saccade (when visual information is suppressed). Indeed when participants were questioned as to whether they noticed anything unusual during the experiment, very few reported noticing anything and those who did notice something suggested it occurred in a very small number of trials (less than 4 trials) and were unable to explain what had happened.

Table 3.1. Examples of the target word manipulation. Sentence frames included an identical preview, a transposed-letter preview, or a substituted-letter preview.

	Example sentence
Identical	`During the earthquake the table` *`nearly`* `collapsed on him.`
Transposed	`During the earthquake the table` *`enarly`* `collapsed on him.`
Substituted	`During the earthquake the table` *`acarly`* `collapsed on him.`

3.2.4 Offline measures of reading ability and IQ

As discussed in Chapter 2, all participants completed a range of offline tests to validate that they were allocated to the correct reading group and to further assess their reading and intelligence profiles. IQ was measured using two subtests of the Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler, 1999); i) the vocabulary subtest, ii) the matrix reasoning subtest (for the full details on the WASI IQ test, refer back to Chapter 2). The Test of Word Reading Efficiency (TOWRE; Torgesen et al., 1999) was conducted to provide information on the participants' reading ability. Indeed, as discussed in Chapter 2, reading ability is best assessed through the combination of both word reading and pseudoword reading. Thus the TOWRE was selected to explore reading ability for adults, as it is formed of two parts; the sight word efficiency test and the phonemic decoding efficiency test, which together provide an overall word reading efficiency standard score for each participant. For both subtests, participants are required to read aloud as many items as possible within 45 seconds. The sight word efficiency subtest is a list of real words and the phonemic decoding efficiency subtest is a list of pseudowords. Finally, all participants completed the Number and Letters measures of the Rapid Automatised Naming (RAN; Wolf & Denckla, 2005) test in which they were required to read an array of letters or numbers presented within rows, as quickly and correctly as possible (again see Chapter 2 for discussion of the use of RAN as an offline measure). The time taken to correctly read aloud the items provides the RAN score and is an indication of how well individuals can integrate both visual and language information.

3.2.5 Procedure

Participants sat in front of a computer screen with their head positioned in a forehead and chin rest to minimise head movements. They were instructed to read the sentences silently for comprehension and to press a button on a gamepad once they had finished reading. A 3-point calibration was conducted prior to the experimental trials and selected due to the horizontal nature of single line sentences; an accurate calibration was accepted when the average errors in the validation were below 0.3° of visual angle. Calibrations were confirmed throughout the experiment and repeated when required. Each trial began with a gaze contingent box (a small black square) presented on the left hand side of the screen, positioned so that the initial letter of the sentence occupied the same location. Once the participant had fixated the square for 250ms, the sentence appeared on the screen. Participants then read the sentence silently and terminated the trial with a button press. After 25% of the experimental sentences a “yes/ no” comprehension question appeared; participants were required to press a corresponding button to answer the question.

3.2.6 Statistical analysis

Prior to the analysis, fixations less than 80ms were either merged into nearby longer fixations or excluded and fixations more than 800ms were excluded from the data set

(5.07 % of fixations). Additional trials were excluded based upon the following criteria; 1) when the boundary was triggered prior to a saccade being made across the boundary, 2) when the display change completed more than 10ms after a fixation landing on the target word, 3) when the end of a saccade briefly crossed the boundary but the successive fixation remained in a position before the boundary, 4) when participants blinked on either the pre-target or target word, 5) when the participants skipped either the pre-target or target word. In total 1,937 trials were removed from the analyses (31.66 % of the dataset), data were excluded similarly across groups and conditions.

3.3 Results

As discussed in Chapter 2, analyses were conducted for both global and local eye movement measures. Global measures refer to results from all of the fixations within the sentence, whereas local measures were based solely on the eye movements that occurred on the target word. Data were analysed using linear mixed models (LMMs; see Chapter 2 for further discussion on the use of LMMs) using the lme4 package (version 1.1.442) in R (version 3.4.4). For global analyses, reading group was the fixed factor for all models. For local analyses, both reading group and preview condition were fixed factors for all models. Participants and items were specified as random effects for both global and local analyses. For each dependent measure, a "full" random structure was implemented including all varying intercepts and slopes of the main effects and interaction (maximal random effects structure as suggested by Barr et al., 2013). If the "full" model failed to converge, or there were too many parameters to fit the data (as indicated by correlations of 0.99, 1, -0.99 or -1 in the random structure), the random structure was systematically trimmed (first by removing correlations between random effects, and if necessary also by removing their interactions). Given our specific predictions, successive difference contrasts were used for preview condition (comparing identical previews and transposed-letter previews, followed by transposed-letter previews and substituted-letter previews). Treatment contrasts were used for Reading group with Skilled Readers (SR) set as the baseline. For each contrast we report beta values (*b*), standard error (SE) and *t* or *z* statistics. Fixation time analyses were carried out on log-transformed models to increase normality and count data were analysed using generalised linear mixed models following a Poisson distribution (GLMMs).

3.3.1 Eye tracking comprehension questions

To ensure participants were reading the sentences, mean accuracy scores for the comprehension questions were recorded for each reading group. The mean accuracy in comprehension score was 95.83% correct for dyslexic readers and 96.82% for skilled adult readers. There was no significant difference in the accuracy scores for comprehension for the two reading groups, $t(49) = -.72$, $p=.478$. Both reading groups were able to read these sentences in order to correctly respond to the comprehension questions.

3.3.2 Off-line measures of reading ability and IQ

Mean scores and statistical analyses for the offline tests are presented in Table 3.2. There were no significant differences in the IQ scores of the two groups. However, the adults with dyslexia scored significantly lower on the TOWRE compared to the skilled adult readers. Scores for both the number and letter subsets of the RAN were also significantly lower for adults with dyslexia compared to skilled adult readers. Thus dyslexic readers showed similar levels of general intelligence to skilled readers, but poor reading and rapid naming skills.

Table 3.2. Mean scores and statistical analysis for the offline tests for adults with and without dyslexia. Standard scores are provided for IQ, reading ability (measured via the TOWRE) and RAN numbers and letters. Standard deviations are shown in parentheses.

	Dyslexic Readers	Skilled Readers	t-test result
IQ	105.40 (7.92)	108.08 (6.36)	$t(49)= -1.33$, $p=.188$
TOWRE	82.60 (11.43)	102.15 (12.67)	$t(49)= -5.78$, $p<.001$ ***
RAN Numbers	103.92 (3.87)	111.38 (3.81)	$t(49)= -6.94$, $p<.001$ ***
RAN Letters	101.16 (5.94)	109.12 (4.59)	$t(49)= -5.36$, $p<.001$ ***

3.3.3 Global measures

The following global measures were included; total sentence reading time, average saccade amplitude, average forward and regressive fixation duration, and total number of forward and regressive fixations per sentence (See Table 3.3 for means and Table 3.4 and Table 3.5 for model outputs). Forward and regressive fixations were classified based upon the previous saccade direction (fixations preceded by a rightward saccade are considered forward fixations and fixations preceded by a leftward saccade are referred to as regressive fixations).

Total reading time: As predicted, there was a main effect of reading group whereby dyslexic readers had significantly longer total reading times than the skilled readers; indicating dyslexic readers take longer to read than non-dyslexic readers.

Saccade amplitude: Whilst there was a numerical trend to support dyslexic readers having shorter saccades than skilled readers, there was, however, no significant difference in saccade amplitude for dyslexic readers compared to skilled readers. Therefore, on average, dyslexic and non-dyslexic readers made saccades of a similar length.

Forward and regressive fixation durations: There was a main effect of group for both forward fixation duration and regressive fixation duration. Dyslexic readers made longer forward fixations and longer regressive fixations compared to the skilled adult readers.

Forward and regressive fixation counts: As predicted, dyslexic readers made significantly more forward fixations and regressive fixations compared to the number of fixations made by skilled readers.

Table 3.3. Average global reading measures. Total reading time (ms), saccade amplitude (degrees), average fixation duration (ms) and number of fixations, for adults with dyslexia (DR) and skilled adult readers (SR).

	Total Time		Saccade Amplitude		Fixation Duration				Fixation Count			
					Forward		Regressive		Forward		Regressive	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
Dyslexic readers	4252	1813	2.58	0.73	236	39	227	65	10.83	3.77	3.96	2.75
Skilled readers	2872	1151	2.75	0.77	218	35	207	69	8.95	2.46	2.34	1.61

Table 3.4. Model output for LMMs conducted for global reading measures of total reading time (ms), saccade amplitude (degrees), average forward fixation duration (ms) and average regressive fixation duration. Significant t values ($|t| \geq 1.96$) are marked in **bold**.

	Total Time			Average saccade amplitude			Forward fixation duration			Regressive fixation duration		
	b	SE	*t*	*b*	SE	*t*	*b*	SE	*t*	*b*	SE	*t*
Intercept	7.89	0.04	**181.30**	0.99	0.04	**26.09**	5.37	0.02	**268.97**	5.27	0.02	**257.67**
Dyslexic readers	0.40	0.06	**6.57**	-0.07	0.05	-1.26	0.08	0.03	**2.80**	0.11	0.03	**3.83**

Table 3.5. Model output for GLMMs conducted for global reading measures of forward fixation count and regressive fixation count. Significant z values (|z| ≥ 1.96) are marked in **bold**.

	Forward fixation count			Regressive fixation count		
	b	SE	*z*	*b*	SE	*z*
Intercept	2.16	0.04	**57.72**	0.77	0.06	**12.15**
Dyslexic readers	0.20	0.05	**3.71**	0.54	0.09	**6.20**

3.3.4 Local measures

The following measures were analyzed for the embedded target words; first fixation duration, single fixation duration, gaze duration, go-past time, total reading time and landing position. First fixation duration is the duration of the initial fixation on the target word. Single fixation duration represents those fixations for which the reader made only one fixation on the target word during first pass. Gaze duration is the sum of fixation durations on the target word before the reader leaves that word. Go-past time is the sum of fixations durations on the target word from when a reader first fixated that word until their first fixation to the right of that word (including any regressions made before moving forward past the target word). Total time is the sum of all fixations that occur on the word throughout the whole trial (including any regressive fixations). Landing position is the character location on which the eye fixates. Table 3.6 provides the mean results for first fixation duration, single fixation duration, gaze duration, go-past time, total reading time and landing position across reading group and preview condition. Table 3.7 provides the LMM outputs and Table 3.8 provides LMM outputs for the simple effects analysis for when interactions between group and preview occurred.

Table 3.6. Mean first fixation duration, single fixation duration, gaze duration, go-past time, total reading time and landing position for the target word, as a function of preview condition and reading group. Standard deviations are shown in parentheses.

		Identical Preview	Transposed	Substituted
First fixation duration (ms)				
	Dyslexia	247 (92)	272 (100)	269 (99)
	Skilled Reader	224 (67)	231 (74)	249 (77)
Single fixation duration (ms)				
	Dyslexia	253 (94)	284 (102)	290 (100)
	Skilled Reader	225 (67)	237 (75)	257 (77)
Gaze duration (ms)				
	Dyslexia	298 (152)	337 (145)	340 (148)
	Skilled Reader	253 (103)	261 (101)	286 (105)
Go-Past Time (ms)				
	Dyslexia	406 (383)	434 (280)	478 (343)
	Skilled Reader	300 (212)	303 (218)	346 (197)
Total Time (ms)				
	Dyslexia	436 (296)	476 (268)	495 (291)
	Skilled Reader	317 (222)	344 (157)	343 (158)
Landing Position (characters)				
	Dyslexia	3.28 (1.59)	3.09 (1.49)	3.10 (1.53)
	Skilled Reader	3.51 (1.55)	3.46 (1.61)	3.35 (1.52)

First fixation duration. For first fixation duration, there was a main effect of group in the predicted direction whereby dyslexic readers made longer first fixations on the target word than skilled readers. There was also a main effect of preview whereby transposed-letter previews received shorter fixation durations than substituted-letter previews. The main effect for identical previews compared to transposed-letter previews, however, did not reach significance. In addition, both interactions were significant (see Figure 3.1). The preview benefit in which identical previews had shorter first fixation durations compared to transposed-letter previews was larger for readers with dyslexia than for skilled readers. Furthermore, the TL effect in which transposed-letter previews had shorter fixation durations than substituted-letter previews, only occurred for the skilled adult readers. Simple effects analysis for the TL effect indicated that the dyslexic readers did not show the usual benefit of transposed-letter previews compared to substituted-letter previews. Thus, for first

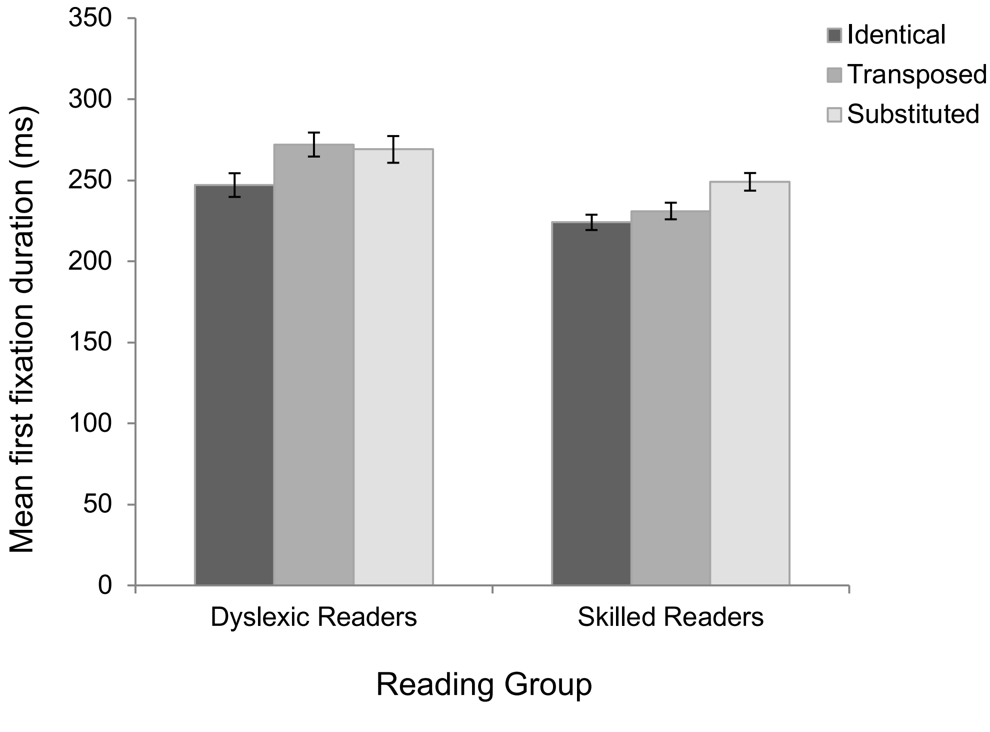

Figure 3.1. Mean first fixation durations for dyslexic readers and skilled readers across identical previews, transposed-letter previews and substituted-letter previews. Error bars show standard error in each preview condition.

fixation duration, skilled adult readers showed the usual orthographic parafoveal preview pattern in which they received the greatest preview benefit from identical previews, followed by transposed-letter preview, with the least benefit for substituted-letter previews; indicating flexible letter position encoding during parafoveal processing. In contrast, dyslexic readers showed a slightly different pattern of results, in which they demonstrated less flexibility when encoding letter position; readers with dyslexia showed a larger preview benefit for identical previews compared to transposed-letter previews than skilled readers and dyslexic readers did not show the usual benefit of transposed-letter previews compared to substituted-letter previews.

Single fixation duration: The single fixation results were very similar to the first fixation duration results. Dyslexic readers demonstrated the usual effect of group in which they made longer single fixations on the target word than skilled readers. In addition, there were main effects of preview where identical previews received shorter fixation durations than transposed-letter previews and transposed-letter previews received shorter fixation durations than substituted-letter previews. Both the interactions were also significant; dyslexic readers showed a greater benefit of identical previews compared to transposed-letter previews than the skilled readers, and, skilled adult readers showed a greater benefit of transposed-letter previews compared to substituted-letters compared to the dyslexic readers. Similar to first fixation duration, the simple effects analysis indicated that dyslexic readers did not show a significant TL effect (see Figure 3.2). This further indicates that, in contrast to skilled readers, dyslexic readers have difficulty with flexibly encoding orthographic information from the parafovea.

Gaze duration: As predicted, dyslexic readers' gaze durations were longer than skilled readers' gaze durations, further indicating their difficulties with reading. The main effect for identical previews compared to transposed-letter previews was marginally significant, indicating such that gaze durations were shorter for identical previews. There was also a significant main effect demonstrating shorter gaze durations following transposed-letter previews than substituted-letter previews. There was an interaction whereby dyslexic readers showed a greater benefit for identical previews compared to transposed-letter previews than did skilled readers. The interaction comparing transposed-letter previews to substituted-letter previews across reading group was also significant. Although dyslexic readers showed a numerical trend to support a benefit of transposed-letter previews compared to substituted-letter previews, simple effects analyses indicated that the benefit of transposed-letter previews compared to substituted-letter previews did not reach significance for dyslexic readers. Thus providing further evidence that dyslexic readers have difficulty with flexibly encoding orthographic parafoveal information.

Go-past time: Similarly to the previous measures reported thus far, readers with dyslexia had longer go-past times than the skilled readers. There was a main effect in which transposed-letter previews required shorter go-past times compared to substituted-letter previews. The main effect of identical previews receiving shorter go-past times than transposed-letter previews was not significant, there was, however, a marginally significant interaction whereby dyslexic readers showed a greater benefit for identical previews compared to transposed-letter previews than skilled readers. The interaction comparing transposed-letter previews to substituted-

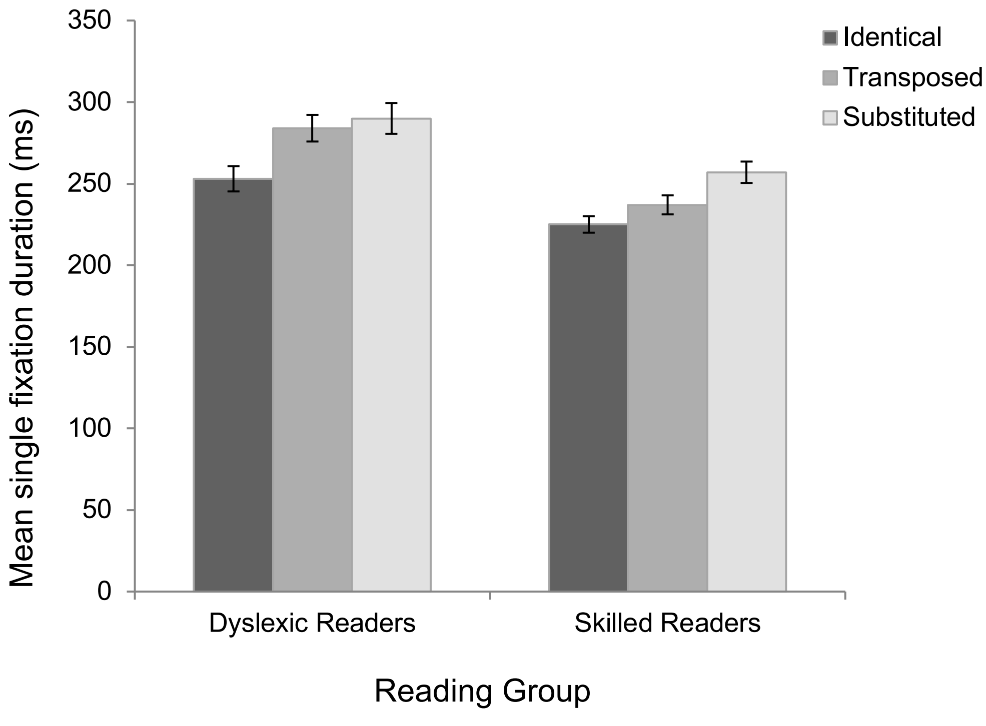

Figure 3.2. Mean single fixation durations for dyslexic readers and skilled readers across identical previews, transposed-letter previews and substituted-letter previews. Error bars show standard error in each preview condition.

letter previews across reading group was not significant. Therefore, for go-past time, dyslexic readers showed the usual orthographic parafoveal preview pattern, in which they received the greatest preview benefit from identical previews, followed by transposed-letter preview, with the least benefit for substituted-letter previews; this indicates flexible letter position encoding during parafoveal processing.

Total reading time: Again, we found a group effect in which dyslexic readers had longer total reading times than skilled readers. For total reading time, there was also a main effect whereby transposed-letter previews had shorter total reading times than substituted-letter previews. The main effect comparing total reading times for identical previews and transposed-letter previews was not significant, however, there was a significant interaction to indicate that dyslexic readers showed a greater benefit for identical previews compared to transposed-letter previews than skilled readers. The interaction comparing transposed-letter previews to substituted-letter previews across reading group was not significant. These results for both dyslexic and non dyslexic readers demonstrate the typical orthographic parafoveal preview effects in which identical previews have the shortest total reading times, followed by transposed-letter previews, with substituted-letter previews having the longest total reading times.

Landing position: There was a marginally significant main effect of group on landing position; dyslexic readers were found to land earlier into the target word than the skilled adult readers. In contrast to the effect of group, preview condition had no significant effect upon landing position. Furthermore, none of the interactions were significant.

Table 3.7. Model output for LMMs conducted for local reading measures of first fixation duration (ms), single fixation duration (ms), gaze duration (ms), go-past time (ms), total reading time (ms) and landing position (characters) on identical previews (IP), transposed-letter previews (TL) and substituted-letter previews (SL). Significant t values (≥ 1.96 of standard error, SE) are marked in **bold**.

	First fixation duration			Single fixation duration			Gaze duration			Go-past time		
	b	SE	*t*	*b*	SE	*t*	*b*	SE	*t*	*b*	SE	*t*
Intercept	5.41	0.02	**236.97**	5.44	0.02	**223.66**	5.52	0.03	**201.16**	5.63	0.04	**157.58**
IP vs TL	0.03	0.02	1.46	0.05	0.02	**2.67**	0.04	0.02	1.84	0.04	0.03	1.18
TL vs SL	0.08	0.02	**3.97**	0.09	0.02	**4.15**	0.10	0.02	**4.37**	0.14	0.03	**4.55**
Dyslexic readers	0.09	0.03	**2.81**	0.11	0.03	**3.35**	0.17	0.04	**4.61**	0.28	0.05	**5.80**
IP vs TL: Dyslexic readers	0.07	0.03	**2.24**	0.07	0.03	**2.35**	0.10	0.03	**3.05**	0.08	0.05	1.81
TL vs SL: Dyslexic readers	-0.09	0.03	**-3.31**	-0.08	0.03	**-2.55**	-0.09	0.03	**-2.71**	-0.06	0.04	-1.33

Table 3.7 continued.

	Total time			Landing Position		
	b	SE	*t*	*b*	SE	*t*
Intercept	5.68	0.04	**146.47**	3.46	0.11	**32.54**
IP vs TL	0.03	0.03	1.16	-0.03	0.11	-0.24
TL vs SL	0.10	0.03	**3.64**	-0.14	0.10	-1.43
Dyslexic readers	0.34	0.05	**6.42**	-0.29	0.15	**-1.92**
IP vs TL: Dyslexic readers	0.08	0.04	1.84	-0.19	0.16	-1.19
TL vs SL: Dyslexic readers	-0.06	0.04	-1.58	0.17	0.14	1.19

Table 3.8. LMM output for simple effects analysis exploring transposed-letter previews (TL) compared to substituted-letter previews (SL) for dyslexic readers in measures of first fixation duration (ms), single fixation duration (ms) and gaze duration (ms). Significant t values ($|t| \geq 1.96$) are marked in **bold**.

	First fixation duration			Single fixation duration			Gaze duration		
	b	SE	*t*	*b*	SE	*t*	*b*	SE	*t*
Intercept	5.45	0.02	**307.31**	5.47	1.94	**282.4**	5.60	2.38	**235.72**
TL vs SL	-0.01	0.02	-0.68	8.66	2.16	0.69	9.72	2.19	0.66

3.4 Discussion

The aim of the current study was to examine parafoveal processing in dyslexic reading; particularly, to examine parafoveal letter position and letter identity encoding in adults with dyslexia. The pattern of results indicated that both dyslexic and skilled adult readers gain preview benefit during reading; however, when presented with identical previews compared to transposed-letter previews, dyslexic readers often exhibited a larger parafoveal preview benefit compared to skilled readers. In addition to demonstrating an increased preview benefit for identical previews compared to transposed-letter previews, dyslexic readers did not demonstrate a TL effect during early reading measures. The TL effect only became significant for dyslexic readers in later measures of reading such as go-past time and total reading time. Finally, in regard to foveal eye movement patterns, dyslexic readers required longer viewing durations and made more fixations than skilled adult readers.

The results from the current study provide initial evidence that dyslexic readers are able to gain parafoveal preview benefit during silent sentence reading. This finding supports and extends the evidence that dyslexic readers parafoveally process information during RAN (Jones et al., 2013; Yan et al., 2013). The current findings, however, show a different pattern of preview benefit effects to those reported by Chace et al. (2005), who concluded that their sample of less skilled readers did not benefit from parafoveal information during silent sentence reading. This is, perhaps, not that surprising since the current experimental design was optimised to find parafoveal preview benefits for readers with dyslexia; specifically, the experiment was designed so that the parafoveal manipulation occurred within the initial two letters and both pre-target and target words were high frequency words which reduce foveal demand and attentional constraints. In contrast, Chace et al. (2005) used low frequency pre-target words, which would demand an increased foveal load in comparison to the high frequency pre-target words selected within the current study. As such, it is possible that the experimental design of the study by Chace et al. (2005) restricted the reader's attentional resources and prevented parafoveal preview benefits, whereas the current experimental design did not. In addition, the two experiments differed in regard to samples. The current experiment focused upon readers with dyslexia whereas Chace et al. (2005) used a sample of readers with poor vocabulary and reading comprehension (often named poor comprehenders). Therefore, it is possible that these two reading groups show differences in their ability to parafoveally process information during reading; this is somewhat supported by studies that indicate that dyslexia and poor comprehenders are considered separate reading disorders with different causes and different treatments (Cain et al., 2000; Cain, 2010; Hulme & Snowling, 2009; Nation et al., 1999; Nation & Snowling, 1998b; Snowling & Hulme, 2012; Stothard & Hulme, 1995). Indeed, within the current study, readers with dyslexia had the attentional resources available to allow them to gain useful information from the parafovea during reading.

Further to examining whether dyslexic readers gain parafoveal preview benefit during reading, the current study explored how attention allocation may impact parafoveal orthographic encoding for the initial letters of the parafoveal word. Contrary to the first prediction that dyslexic readers may have difficulty with letter position encoding (Vidyasagar & Pammer, 2010; Whitney & Cornelissen, 2005) and therefore show similar preview benefit for both identical previews and transposed-letter previews, the present findings demonstrate that both groups of readers showed greater preview benefit for identical previews compared to transposed-letter previews. This supports research demonstrating that letter-position information is encoded from the initial letters within the parafoveal word for skilled readers (Johnson et al., 2007; Pagán et al., 2016; Tiffin-Richards & Schroeder, 2015). Furthermore, the current results provide evidence that dyslexic readers do in fact encode letter position from the initial letters of the parafoveal word. This finding suggests that not only are adult dyslexic readers able to allocate their attention to the parafovea for pre-processing, but also individually to the initial letters within the parafoveal word in order to encode letter position information. Dyslexic readers, however, often demonstrated an increased benefit of identical previews compared to transposed-letter previews relative to that of the skilled adult readers. Indeed, consistent with prior research (Johnson & Dunne, 2011; Johnson et al., 2007) we found that, for skilled readers, transposed-letter previews were almost as beneficial to lexical identification as identical previews. Dyslexic readers, however, demonstrated a significantly greater benefit of identical previews compared to transposed letter previews in comparison to skilled readers. This suggests that dyslexic readers show reduced lexical activation for transposed-letter previews than that of the skilled readers; dyslexic readers, therefore, have less flexible letter position encoding, in which previews with transposed letters provide a reduced lexical activation to the base word, than that found for skilled adult readers.

In support of previous studies in skilled adult parafoveal processing (Johnson et al., 2007; Pagán et al., 2016), the current results also provide evidence of a TL effect (preview benefit for transposed letter previews compared to substituted letter previews) in skilled adult readers, thus demonstrating that skilled adult readers can encode letter identity independently to letter position. For dyslexic readers, however, there was a slightly different pattern of results. The increased preview benefit that occurred for identical previews compared to transposed-letter previews, specifically for dyslexic readers, occurred alongside a reduced difference between transposed-letter previews and substituted-letter previews (the TL effect) for the dyslexic readers. Thus, dyslexic readers did not demonstrate a TL effect in early measures of reading and the TL effect only became significant in later reading measures (go past time and total reading time). For first fixation duration, dyslexic readers did not show a numerical trend to support the TL effect, indicating that dyslexic readers rely more heavily upon correct letter position information than skilled readers, during early measures of reading. In measures of single fixation duration and gaze duration, dyslexic readers showed a numerical trend to support the TL effect but, through further exploration using simple effects, this effect was not significant for dyslexic readers. For go-past time and total reading time, however, readers with dyslexia exhibited a significant TL effect.

The fact that the TL effect is significant in go-past time suggests that dyslexic readers start to flexibly encode letter position in first pass within word regressions rather than during early reading measures. Whilst this is a later measure than one would typically expected to find parafoveal preview benefits, this is perhaps not that surprising for dyslexic readers who have slower lexical activation and make more fixations (both forward and regressive) compared to skilled adult readers. Thus, for dyslexic readers, successful lexical activation often occurs from multiple fixations. Furthermore, as discussed, dyslexic adults showed an increased dependence on letter position for lexical activation of parafoveal information compared to skilled adult readers. As such, flexible encoding of letter position and letter identity may not be as useful for dyslexic readers in early measures of reading. Therefore, whilst dyslexic readers did show a TL effect, indicating that they can use a flexible letter position encoding mechanism, they are, however, less efficient at processing correct letter identity information when it is in the incorrect letter position, causing the TL effects to occur within later eye movement measures. Indeed, it may be the case that the incorrect letter identities encoded in a substituted-letter preview disrupt lexical activation during these later measures, whereas the transposed-letter previews provide the correct letter identities and thus cause less disruption to lexical activation.

Although dyslexic readers demonstrated a greater dependence on letter position information and a delayed TL effect relative to skilled adult readers, dyslexic readers did show a trend toward a benefit of transposed-letter previews compared to substituted-letter previews in single fixation duration and gaze duration as well as significant effects n go-past time and total reading time. As such, we suggest that dyslexic readers are not using a whole word encoding method as suggested by Whitney and Cornelissen (2005) but are, in fact, using a flexible letter position coding mechanism with greater dependence upon correct letter position information compared to skilled readers. Such pattern of results could be explained by dyslexic readers' reduced reading skills; dyslexic readers are demonstrating a serial reading pattern similar to younger readers, who rely more upon encoding individuals letters within a word (Ehri, 2005; 2010), therefore letter position information is more important to lexical activation. Such explanation is in line with the proposal that the eye movement patterns of dyslexic readers indicate their linguistic processing difficulties (Kirkby et al., 2008). Furthermore, the reduced TL effect for dyslexic readers could also highlight that dyslexic readers have a deficit in attention allocation, whereby they have not developed the correct attentional location gradient to allow them to flexibility encode letter position information (Vidyasagar & Pammer, 2010; Whitney & Cornelissen, 2005). It is, however, currently unclear the extent to which this attentional allocation deficit may be specific to dyslexic readers rather than to poor readers more generally.

Indeed, it is important to note that the greater dependence on correct letter position information, found for dyslexic readers compared to non-dyslexic readers, might be a finding limited to these initial letters. Recall that the current experiment specifically manipulated the initial letters within the parafoveal word. Initial letters of a word are, however, encoded less flexibly than internal letters, demonstrating an intrinsic importance of initial letters for lexical identification (Johnson & Dunne, 2012; Johnson & Eisler, 2012; Johnson et al., 2007; Tiffin-Richards & Schroeder, 2015; White et al., 2008). Here we show that dyslexic readers have a greater reliance on these initial letter positions for lexical word identification compared to skilled adult readers. Therefore, it may be that readers with dyslexia show an increased importance for these initial letters compared to skilled readers. We suggest that these initial letters may be intrinsically important due to the requirement for sequential activation of phonological codes in order to activate phonological representations during reading. Dyslexic readers, due to their difficulties in phonological processing (Snowling, 2000), may therefore have a greater reliance upon the correct initial letter position information, as they have specific difficulties with encoding phonological information compared to skilled adult readers. Thus, disruptions in the sequential order of phonological information, as found in transposed-letters, may be more costly to dyslexic readers than skilled readers.

Finally, in addition to exploring parafoveal processing for readers with dyslexia, the current study also recorded measures of foveal processing. In line with previous research into dyslexic eye movements during reading (Hawelka et al., 2010; Kirkby et al., 2011; Kirkby et al., 2008), the present study found the usual effects of reading ability on eye movement behaviour. Dyslexic readers required longer viewing durations than the skilled adult readers and this occurred at both global (average regressive fixation duration and total reading time) and local levels (first fixation duration, single fixation duration, gaze duration and total reading time). Dyslexic readers also required more forward fixations and more regressive fixations than skilled adult readers at a global level. Altogether, these differences in eye movement behaviour for dyslexic compared to non-dyslexic readers indicate that the current sample of dyslexic readers showed reading difficulties compared to the sample of non-dyslexic adult readers, thus providing further evidence of dyslexic readers' difficulties with lexical processing in comparison to skilled readers (Hawelka et al., 2010).

In addition to the above eye movement patterns, dyslexic readers also showed differences in landing position; dyslexic readers landed earlier into the target word compared to skilled adult readers. Whilst earlier landing positions are often found for readers with dyslexia relative to non-dyslexic readers (De Luca et al., 2002; Hawelka et al., 2010; MacKeben et al., 2004; Pan et al., 2014), it is less clear as to why readers with dyslexia make these early landing positions. One explanation is that dyslexic readers do not receive sufficient parafoveal information to correctly target their saccades; indeed, parafoveal information is typically used to help guide eye movements (Rayner, 1998; Sereno & Rayner, 2000). Within the current study, however, dyslexic readers showed the ability to allocate their attention to the parafovea, in order to extract useful information from the parafovea during reading (however, note the parafoveal manipulations only occurred within the first two letters of the parafoveal word and, as such, it is possible that parafoveal processing difficulties may occur further into the parafovea). An alternative explanation is that dyslexic readers develop a reading strategy, which impacts their landing positions. Specifically, it has been suggested that the frequent orthographic recognition failures made by readers with dyslexia may have resulted in a general tendency to target the beginnings of words in hope to improve reading (Hawelka et al., 2010); this suggestion has been supported by a number of studies (De Luca et al., 2002; MacKeben et al., 2004). Consequently, whilst the current study cannot determine why readers with dyslexia make earlier landing positions, similarly to previous studies, the current study did demonstrate that readers with dyslexia show earlier landing positions compared to skilled adult readers.

Whilst the current research provides initial evidence in regard to parafoveal processing during reading for adults with dyslexia, future work is required to extend these findings and further understand why dyslexic readers exhibit differences in parafoveal processing relative to skilled adult readers. In fact, future work would benefit from exploring whether readers with dyslexia can extend their parafoveal processing abilities beyond the initial letters of the parafovea and, if so, whether they show similarly reduced TL effects for internal letter transpositions. Since this initial study was designed to determine whether readers with dyslexia do gain parafoveal processing benefit during reading, the foveal demands were kept low (with a high frequency pre-target word), it is possible that when foveal demand is increased, dyslexic readers show limitations in parafoveal processing.

3.5 Chapter summary

This chapter reported the first Experiment of the thesis, which explored orthographic parafoveal processing for adult readers with dyslexia compared to skilled adult readers. In sum, this chapter provided initial evidence that dyslexic readers were able to allocate their attention to the parafoveal word in order to gain parafoveal preview benefits during reading. Specifically, readers with dyslexia were able to allocate their attention to individual letters within the parafoveal word in order to encode both letter position and letter identity. However, whilst readers with dyslexia appear to use a flexible letter position encoding mechanism (in which letter identity and letter position are encoded independently), they showed a greater dependence upon correct letter position information, compared to skilled readers. Consequently, contrary to the predictions, dyslexic readers were able to allocate their attention to the parafoveal word in order to encode letter identity and letter position information during reading, but, they appeared to rely more on letter position information for lexical activation compared to skilled adult readers. Therefore, although dyslexic readers were able to allocate their attention to the parafovea, they may have an attention deficit in which they have not developed the correct attentional location gradient to allow for the flexible encoding of letter position information that occurs within skilled adult readers (Vidyasagar & Pammer, 2010; Whitney & Cornelissen, 2005). However, note that the current results cannot determine the cause of such difficulties; these results may also be explained by dyslexic readers' reduced reading skills compared to skilled readers, or, due to dyslexic readers showing increased importance for initial letters due to their difficulties in phonological processing. Whilst this initial experiment provides evidence of orthographic parafoveal processing during dyslexic reading, it is still unclear to what extent attention deficits may impact readers with dyslexia and whether such attention deficits are specific to dyslexic readers, or due to their poor reading skills.

The next chapter extends this work to examine attention allocation and parafoveal processing for children with dyslexia. Chapter 4 explores orthographic parafoveal processing in children with dyslexia, children matched for reading age and children matched for chronological age. This allows for further understanding of how deficits in reading ability may impact dyslexic reading.

Chapter Four: Experiment 2

4.0 Chapter overview

Whilst Chapter 3 provides initial evidence for dyslexic parafoveal processing during reading, adult dyslexic readers showed a greater reliance on letter position information for lexical identification of parafoveal information compared to skilled adult readers. Within this chapter, the same experimental design was used to explore parafoveal processing and orthographic encoding of letter identity and letter position information for children with dyslexia. This not only allowed for the findings to be extended to child populations, but also served to examine the relationship between dyslexic parafoveal processing and reading ability, through the use of two control groups; typically developing children with a similar chronological age to the dyslexic children and typically developing children with a reading age similar to the dyslexic children (see Chapter 2 for discussion about the importance of testing with both adult and child samples and also experimental controls groups). Thus, the following chapter used the boundary paradigm to explore whether both dyslexic and groups of non-dyslexic children can parafoveally encode letter identity and letter position during reading.

Orthographic parafoveal processing in children with and without dyslexia

4.1 Introduction

Whilst there is a growing body of research into parafoveal processing for skilled adult readers (see Schotter et al., 2012 for a review), there is still a limited amount of research exploring the development of parafoveal processing for child readers (Häikiö et al., 2010; Marx et al., 2015; Pagán et al., 2016; Tiffin-Richards & Schroeder, 2015). As discussed in Chapter 1, the perceptual span increases during development and this increase in perceptual span is largely assigned to developments in reading ability (Häikiö et al., 2009; Rayner, 1986). In fact the perceptual span plateaus by the age of 11 years old when children show a perceptual span similar to that of adults (Häikiö et al., 2009; Marx et al., 2016; Rayner, 1986; Sperlich et al., 2015). In addition to understanding the development of the perceptual span, recent research has started to use the boundary paradigm to explore parafoveal processing benefits of children during reading (Häikiö et al., 2010; Marx et al., 2015; Pagán et al., 2015; Tiffin-Richards & Schroeder, 2015). To date, there is evidence of parafoveal preview benefits for child readers; specifically, orthographic and phonological parafoveal processing have been found to occur in typically developing readers as young as 8 years old (Pagán et al., 2015; Tiffin-Richards & Schroeder, 2015).

Marx et al. (2015) used the boundary paradigm to explore parafoveal processing for German-speaking children in grade 4 (mean age 10 years old) and grade 6 (mean age 12 years old). They used parafoveal masking, a paradigm in which valid previews are compared to previews that are 'masked' to prevent parafoveal processing. Within their study they implemented a novel masking technique in which the salience of the preview was manipulated by systematically degrading the perceptibility of the preview; black pixels from the letters were randomly exchanged for white pixels from the nearby area thus making the words look somewhat blurred. Up until recent years, there was very limited research on parafoveal processing in children. Marx et al. (2015) developed their predictions based upon two studies, Zoccolotti et al. (2013) and Häikiö et al. (2009). Zoccolotti et al. (2013) found that 12 year olds read words faster when they are presented in list format, compared to words presented in isolation, a finding that was taken as evidence of parafoveal processing in children aged 12 years old. In addition, Häikiö et al. (2009) reported that the letter identity span of 10 year olds (4th grade children) was restricted to seven letters where as the span of 12 year olds (6th grade children) was much more similar to adults at nine letters. Marx et al. (2015) predicted preview benefit effects for 12 year old children but less preview benefit for 10 year old children. In fact, Marx et al. found evidence for parafoveal processing in both groups of children and, contrary to their predictions, there were no differences in the amount of preview benefit that the two groups received. This may be explained by the fact that child readers around the age of 11 years old show similar eye movement patterns and perceptual span to skilled adult readers (Blythe & Joseph, 2011: Häikiö et al., 2009; Rayner, 1986; Sperlich et al., 2015). In which case, it is possible that both the 10 year old and 12 year old children were reading at a level at which they show similar parafoveal processing abilities to adult readers.

Häikiö et al. (2010) also found evidence of parafoveal processing in typically developing Finnish children (age 8 years old, 10 years old and 12 years old) and adults. More specifically, they used the boundary paradigm to examine whether children and adults extract more parafoveal information from the second part of a compound word than from the same word when it forms part of an adjective-noun phrase. The results showed that all age groups were able to extract information from the parafovea, and more parafoveal information was extracted within compound words than across two separate words. They used these results to conclude that all reading groups were able to allocate their attention to the parafovea in order to encode useful information and that attention allocation was influenced by words that are more linguistically and spatially integrated.

Whilst Häikiö et al. (2010) predicted that beginning readers (8 year old children) would show a different pattern of preview benefit compared to the more skilled reading groups (10 and 12 year old children; in line with results from Häikiö et al., 2009), they found consistent preview benefit across both younger and older children. As such, even children as young as 8 years old were able to allocate their attention to the parafoveal word in order to gain preview benefit and greater preview benefit from a compound word than from an adjective-noun phrase. This may, therefore, indicate sufficient parafoveal processing abilities develop as young as 8 years old. However, the authors suggest that a lack of significant difference between the groups could be due to the stimuli used within their experiment. The sentences used within their study were designed to be particularly easy to read and this may have enabled the younger readers to allocate their attention further into the perceptual span to such an extent that parafoveal manipulations affected all groups of readers in a similar manner. In which case, they suggested that, if the reading task was made more challenging, such as paragraph reading in Häikiö et al. (2009), there may be variation in the parafoveal processing of children at different ages. In favourable reading conditions, however, children as young as 8 years old show the ability to parafoveally process information during reading in a similar manner to more skilled reading children; therefore, reading ability may only impact the ability to parafoveally process information during reading when attentional demands are increased.

Of greater interest to the current line of enquiry are the studies by Tiffin-Richards and Schroeder (2015) and Pagán et al. (2016) who explored parafoveal processing of orthographic information (letter identity and letter position) during reading. Both studies used the TL (transposed letter) effect to explore letter position encoding during parafoveal processing. Before discussing the development of TL effects within parafoveal processing, research into foveal processing of TL effects within children will be discussed. Indeed, similarly to research with adults, studies of single word recognition have demonstrated that, even for children, non-words with a transposition of two letters (e.g. *jugde*) were found to be more similar to the base word (e.g. *judge*) than non-words with two substituted letters (Acha & Perea, 2008; Castles, Davis, Cavalot, & Forster, 2007; Kohnen & Castles, 2013; Lété & Fayol, 2013; Paterson, Read, McGowan, & Jordan, 2015; Perea & Estévez, 2008). The facilitation that is provided by non-words with transposed letters compared to words with substituted letters is known as the TL effect and indicates that non-words with transposed letters significantly activate the lexical representation of the base word more than non-words with substituted letters. The TL effect demonstrates that letter identity encoding is not specific to letter position – these are encoded independently of one another.

Using a masked priming lexical decision task, Castles et al. (2007) explored transposed-letter and substituted-letter priming in English speaking third grade children (mean age 8 years 6 months) and adults. The third grade children were then tested again once they reached fifth grade (mean age 10 years and 5 months). Castles et al. (2007) used a transposed-letter prime (created by reversing two letters at the beginning, middle, or end of the word), substituted-letter prime (created by replacing one letter with another letter in the first, third, or fifth position) and control prime (in which none of the letters overlapped with the base word) to explore orthographic encoding. Whilst they did not specifically explore the TL effect (i.e. the difference between substituted-letter primes and transposed-letter primes), they did examine both the difference between the control prime and the transposed-letter prime and the difference between the control prime and the substituted-letter prime.

For the adult readers, Castles et al. (2007) found no facilitation for either transposed-letter primes or substituted-letter primes. Such results suggest that adults have a finely tuned word recognition system in which readers have developed an effective mechanism for discriminating between words with a high level of precision; however, as discussed in Chapter 3 there is a body of research finding TL effects in adult readers (Chambers, 1979; Christianson et al., 2005; Forster et al., 1987;

O'Connor & Forster, 1981; Perea & Fraga, 2006; Perea & Lupker, 2003a, 2003b, 2004). For third grade children, Castles et al., (2007) found that both transposed-letter primes and substituted-letter primes provided substantial facilitation to lexical decision responses. Children, therefore, had a much more flexible word recognition system, which was much less finely tuned compared to adult readers. In addition to encoding letter position flexibly, children within grade 3 appeared to tolerate some degree of mismatch in letter identity as well. However, when grade 3 children were tested again in grade 5, Castles et al. (2007) found that children were no longer showing facilitation for the substituted letter prime, nevertheless, they were still gaining facilitation from the transposed-letter prime. Such results suggest that precise letter position encoding develops slower than precise letter identity encoding, and letter position information is encoded flexibly for children in grade 5 (with a mean age of 10 years and 5 months).

Although beginning readers rely upon a letter-by-letter reading technique (Ehri, 2005; 2010), Castles et al. (2007) suggest that children have a more flexible letter position encoding mechanism than skilled readers. In particular, Castles et al. (2007) proposed that because children are less skilled readers, they have a reduced vocabulary and therefore, a smaller range of words within their lexicon. This means that when words are being identified, there are fewer competing lexical entries and words can be identified more flexibly using orthographic information. As such, children are more likely to identify a word with a less accurate overlap of orthographic information than adults who have finely tuned and wide ranging lexical representations. This suggestion is supported by Perea and Estévez (2008) who tasked Spanish beginning (7 year olds), intermediate (9 year olds), and adult readers with reading aloud words with transposed letters (for example CHOLOCATE, where the base word is CHOCOLATE). They demonstrated that beginning readers made more errors (i.e. reading aloud the base word), compared to both intermediate and adult readers; these results provide additional evidence that children have a more flexible letter encoding system.

In a similar line of enquiry to that reported by Castles et al. (2007), Acha and Perea (2008) found that the primary difference in the encoding of transposed-letters between children and adult readers was the magnitude of the TL effect; children showed a larger TL effect compared to adults. Using a masked priming lexical decision task with Spanish beginning (7 years old), intermediate (11 years old) and adult readers, Acha and Perea (2008) found that for all reading groups base words (e.g. animal), which were initially primed by transposed-letter non-words (e.g. aminal), were responded to faster than words which were primed by substituted-letter non-words (e.g. arisal). This demonstrates that children as young as 7 years old, 9 year old children and adults, all showed a benefit of processing transposed-letter words over substituted letter words. Interestingly, Acha and Perea (2008) found that the beginning readers showed a TL effect of greater magnitude compared to both intermediate and adult readers, providing further support for increased flexibility in orthographic processing for less skilled readers.

Whilst studies of single word identification provide a basis for understanding the development of orthographic encoding, there are now a small number of studies that have started to explore the development of orthographic encoding, during parafoveal processing in natural reading tasks. Tiffin-Richards and Schroeder (2015) used the boundary paradigm to explore parafoveal processing in German-speaking children aged 8-9 years in order to assess both phonological and orthographic preview effects. Two sets of sentences were constructed, intermixed and presented to participants. The first set of sentences included a parafoveal manipulation in which the preview could be: an identical preview, a pseudo-homophone or an orthographic control (examples are provided in German; *Reis*, *Rais*, *Ruis*, respectively). In the second set of sentences the parafoveal manipulation was either; an identical preview (target word which had a capitalised first letter, e.g. *Burg*), a lower case preview (where the target word was presented all in lower case, e.g. *burg*), a transposed-letter manipulation (in which the manipulation was presented within the initial letters of the word or internal letters of the word, e.g. *Ubrg* or *Brug*) and a substitution manipulation (where the initial or internal letters of the word were replaced with orthographically similar letters, e.g. *Ohrg* or *Bnog*).

Tiffin-Richards and Schroeder (2015) found evidence of parafoveal processing in child readers. They showed that pseudo-homophone previews differentially influenced children's compared to adult's reading; children appeared to use phonological information from the parafovea whilst adults did not. Adults, however, did receive benefit from orthographic information whereas the children only gained orthographic preview benefit during single fixation durations and such effects were specific to TL-internal and TL-initial preview benefits, where TL conditions provided greater preview benefit than the corresponding substituted letter preview. The author's note that the TL effect found in single fixation duration for children should, however, be interpreted with caution. It is well established that children generally make more fixations during reading as well as more refixations on words than adult readers (Blythe & Joseph, 2011; Reichle et al., 2013). As such, children make fewer single fixations. That said, their findings are consistent with a developmental view of reading that initially depends on phonological processes, and orthographic processes become increasingly important later on in development (Grainger, Lété, Bertand, Dufau, & Ziegler, 2012).

Whilst the results from Tiffin-Richards and Schroeder (2015) provide a useful basis for understanding parafoveal processing in developing readers, the lack of a TL effect found within their child sample contrasts directly with research exploring foveal TL effects in children (Acha & Perea, 2008; Castles et al., 2007; Perea & Estévez, 2008). Indeed, research has found an increased TL effect in children compared to adults during foveal processing (Acha & Perea, 2008; Castles et al., 2007; Perea & Estévez, 2008). Tiffin-Richards and Schroeder (2015), however, only found TL effects for children in single fixation duration and thus concluded that children only make use of flexible orthographic parafoveal information during occasions when the target received only one fixation. Children, therefore, have a reduced flexibility in encoding orthographic information compared to adult readers, except for occasions in which they are able to encode a word within one fixation. This suggests that, for child readers, perhaps TL effects manifest differently across parafoveal processing and foveal processing. Children are developing readers in which reading is a more taxing process; therefore, differences in orthographic encoding during foveal and parafoveal processing may be due to children having reduced attentional resources available to allocate to parafoveal compared to foveal processing. Hence, foveal processing may allow for flexible letter position encoding whereas parafoveal processing may in fact rely more upon correct letter position, except for occasions where the word is easy enough to encode within one fixation. This suggestion is, however, difficult to merge with the finding that these children were able to gain parafoveal preview benefit from phonological information regardless of whether the word was encoded within one or more fixations.

One must consider, however, that Tiffin-Richards and Schroeder's (2015) study was conducted in German, which is a more orthographically transparent language than English. Indeed, languages vary in orthographic depth (McDougall, Brunswick & de Mornay Davies, 2010) and are broadly described in terms of transparent (shallow: e.g. Finnish) or opaque (deep: e.g. English). Within a transparent orthography, each grapheme represents one phoneme and 'sounding out' letters in a word is a successful strategy for reading (McDougall et al., 2010). In contrast, a deep orthographic language has a much more complex mapping of graphemes and phonemes, where several letters often represent one phoneme. Additionally, there are considerably more phonemes than letters, therefore, making letter-sound relationships much less predictable than in transparent orthographies (McDougall et al., 2010). As German is more orthographically transparent than English, there are fewer irregular words (Ziegler, Perry, & Coltheart, 2000) and this is important in regard to the development of orthographic processing and consequently TL effects. Irregular words cannot be correctly pronounced using phonological decoding; therefore, these words are suggested to require greater dependence on orthographic processing. In which case, English readers may show an earlier dependence on orthographic information than was found for German children (Tiffin-Richards & Schroeder, 2015). This suggestion is supported by the work of Pagán et al. (2016) who demonstrated orthographic parafoveal preview benefits for English children as young as 8-9 years old.

Pagán et al. (2016) explored parafoveal processing of both letter identity and letter position information in the initial trigram (three letters) of the parafoveal word. Using the boundary paradigm, they presented English children (aged 8-9 years) and skilled adult readers with the following parafoveal manipulations: identity previews, transposed letter and substituted letter non-words with a manipulation within letter positions 1 and 2, 1 and 3, and, 2 and 3. Pagán et al. (2016) reported that children were able to gain orthographic parafoveal benefit in a similar manner to the adult readers. Children showed a benefit of identity previews compared to substituted and transposed letter previews, and also showed a TL effect (benefit for transposed letters compared to substituted letters). Children were able to encode letter position information independently to letter identity within the parafovea. It must, however, be noted that although the children in the Pagán et al. (2016) study had a mean age of 9 years old, the mean reading age was in fact much higher, at 11 years, which suggests the children who were tested were particularly good readers for their age and, on average, read approximately two years above their chronological age. It is, therefore, difficult to determine whether the parafoveal processing abilities of children in the Pagán et al. (2016) study are due to their chronological age (9 years old) or due to their reading age (11 years old). As such, it is unclear whether children with a reading age of 9 years would demonstrate the same pattern of parafoveal preview effects.

Whilst there is a growing body of research into orthographic parafoveal processing in children, there has been very little research into parafoveal processing for children with dyslexia. There is, however, evidence for transposed-letter priming and substituted-letter priming within foveal processing for readers with dyslexia. Lété and Fayol (2013) conducted a masked priming lexical decision task with typically developing French third grade children (with a mean age of 8 years 11 months and a reading age of 9 years), fifth grade children (with a mean age of 10 years 10 months and a reading age of 11 years 3 months), adults, and dyslexic children from sixth, seventh, and eighth grade (mean age 13 years 1 month and a reading age of 8 years and 6 months) matched for reading age with the typically developing third grade readers. Similarly to that of Castles et al. (2007), Lété and Fayol (2013) used a transposed-letter prime (created by reversing two letters at the beginning, middle, or end of the word), substituted-letter prime (created by replacing one letter with another letter in the first, third, or fifth position) and control prime (in which none of the letters overlapped with the base word) and explored the difference between the control prime and the transposed-letter prime and the difference between the control prime and the substituted-letter prime.

For skilled adult readers, Lété and Fayol (2013) found facilitation for the transposed-letter primes but no facilitation for the substituted-letter primes. In fact, adult readers demonstrated flexible encoding of letter position information in which encoding the correct letter identities is useful, even if they are in the incorrect letter position. In contrast, having incorrect letter identity information does not provide facilitation to lexical identification of the base word as there is a stricter requirement for correct letter identity compared to letter position. In contrast to adults, children in the fifth grade showed facilitation from both transposed-letter primes and substituted-letter primes. Therefore, similarly to the third grade English readers from Castles et al. (2007), fifth grade French readers show flexible orthographic encoding of both letter identity and letter position information. Interestingly, and in contrast to the findings for third grade children in Castles et al. (2007), the third grade children in Lété and Fayol's (2013) study showed no evidence of priming for either transposed-letter or substituted-letter primes, suggesting that these children were either unable to encode any information during priming, or that there is very little flexibility within their orthographic encoding. This indicates that orthographic parafoveal processing develops at different ages in English and French; English children appear to develop flexible orthographic processing younger than French children. Whilst French and English are both considered to be opaque orthographies, the level of phonological consistency within French suggests that the language is quite regular in respect to reading (Ziegler, Stone, & Jacobs, 1997). Orthographic density may, in fact, impact the development of orthographic parafoveal processing. Of particular interest to the current thesis, however, are the results from the children with dyslexia.

Similarly to the children in fifth grade, the dyslexic children showed both priming effects for transposed-letter primes and substituted-letter primes and these effects were at a similar magnitude to that found for the children in fifth grade. Therefore, although the 13-year-old dyslexic readers had similar reading abilities (when evaluated on grapheme-to-phoneme mapping in a reading aloud task) compared to the third grade children (aged 8 years 6 months), they demonstrated similar orthographic processing during masked priming as the fifth grade children (aged 10 years 10 months, with a reading age of 11 years 3 months). This suggests that dyslexic readers have more finely tuned orthographic representations than their reading skill would predict, at least for the high frequency words used within Lété and Fayol's (2013) study. It is interesting to note that the authors claim that the dyslexic readers' orthographic processing was similar to fifth grade children in regard to substituted-letter priming, but suggest that it was in fact less finely tuned (thus more flexible) in the case of transposed-letter priming. Whilst they did not find a significant interaction to support this, dyslexic readers showed a numerical trend to support greater priming effects for transposed-letter primes, compared to fifth grade children. Although non-significant results must be interpreted with caution, such a trend in the pattern of results might lead us to predict that dyslexic children's access to orthographic lexical information is less impoverished than their access to phonological codes, which is a function of their reading ability (see Grainger, Bouttevin, Truc, Bastien, & Ziegler, 2003, and Lété & Ducrot, 2008, for similar conclusions). This is also consistent with Ziegler and Goswami (2005) who proposed that children with dyslexia do not perform worse than children matched on reading age during tasks that require automatic orthographic access to whole words, however, they do show deficits in relation to sublexical phonology.

Whilst Lété and Fayol (2013) provide useful insights into orthographic processing of letter identity and letter position information for dyslexic readers, unfortunately the authors did not include a group of typically developing children matched for chronological age. Therefore, it is impossible to fully understand the developmental trajectory for readers with dyslexia compared to typically developing readers. From their pattern of results, it can be concluded that the dyslexic readers show effects of priming that are different to the children who are matched for reading age (third grade children); however, we cannot determine whether the dyslexic readers are performing similarly to children of the same chronological age. Even when examining previous studies into the development of orthographic processing (Acha & Perea, 2008; Castles et al., 2007; Pagán et al., 2016; Tiffin-Richards & Schroeder, 2015), it is still unclear as to whether dyslexic readers may be performing similarly to a control group of typically developing English children matched for chronological age, as the correct age group has yet to be tested. Furthermore, many studies do not indicate the reading age of their typically developing child samples, making it difficult to understand how the development of orthographic processing occurs alongside both chronological age and reading age. From the research by Lété and Fayol (2013) it is clear that French children with dyslexia show similar patterns of priming to the French children in grade 5; however, the children in grade 5 are younger than the dyslexic readers. Therefore, it may be the case that children with dyslexia show similar patterns to children in grade 5 but deficits in comparison to their peer group. In fact, by age 13, one would predict that typically developing children would show similar patterns of results to adults, in which case typically developing children matched for chronological age would show a priming benefit for TL primes but no priming benefit for SL primes. Such a result would suggest that dyslexic readers would show orthographic processing abilities that are delayed relative to their peers.

Although these results provide a basis from which to understand TL effects in foveal processing for readers with dyslexia, there is currently only one study exploring the TL effect during parafoveal processing for dyslexic readers (the first experiment within this thesis, detailed in Chapter 3). As discussed throughout this thesis, parafoveal processing is particularly interesting in regard to dyslexia, as efficient encoding of parafoveal information requires correct attention allocation and deficits in attention allocation may be causally related to dyslexia (Vidyasagar & Pammer, 2010; Whitney & Cornelissen, 2005). One study, which has explored parafoveal processing for Chinese dyslexic children during RAN, found evidence for less efficient orthographic parafoveal processing in dyslexic children compared to typically developing child readers (Yan et al., 2013). Yan et al. (2013) recorded the eye movements of children with dyslexia and chronological age matched children as they read aloud letters during two rapid automised naming (RAN) tasks; a continuous RAN task (in which all letters were presented at the same time) and a discrete RAN task (where one letter was presented at a time, therefore, removing the possibility of parafoveally processing the next letter). Through including two variations of the RAN task, Yan et al. (2013) were able to determine whether dyslexic readers were making use of the parafoveal information presented during RAN. They found that removing a parafoveal preview of the upcoming letter disrupted both groups of readers, i.e. naming times and viewing durations were longer during the discrete RAN than the continuous RAN. This indicates that children with dyslexia do make use of information in the parafovea. However, Yan et al. (2013) also found an interaction between reading ability and RAN condition, in which children with dyslexia were less disrupted by the discrete RAN task than the typically developing children. Consequently, the authors concluded that children with dyslexia were less efficient in their use of parafoveal information, compared to typically developing children matched for chronological age, and suggested this is probably due to dyslexic readers requiring greater attentional resources for foveal processing. Whilst dyslexic readers showed less efficiency in the parafoveal processing of orthographic information compared to typically developing children matched for chronological age, Once again, due to a lack of the both chronological age and reading age control groups, it is unclear whether such findings may be caused by dyslexic readers' lower reading skill rather than a fundamental difference in their cognitive processing.

Whilst there are currently no studies exploring orthographic parafoveal processing during reading for children with dyslexia, Chapter 3 provides initial evidence of orthographic parafoveal processing during reading for dyslexic adults. Recall, dyslexic adults readers showed parafoveal preview benefits in which they encode both letter identity and letter position, however, dyslexic readers demonstrated a greater reliance on letter position for the lexical identification and delayed flexible letter position encoding (at least for the initial letters of the parafoveal word) compared to skilled adult readers. It was, however, unclear exactly why dyslexic adult readers demonstrated such differences in letter position encoding. As discussed in Chapter 3, such results could be explained by reduced reading skills, in which case dyslexic readers demonstrate a serial reading pattern similar to younger readers (Ehri, 2005; 2010), or, due to a deficit in attention allocation whereby dyslexic readers have not developed the correct attentional location gradient to allow them to flexibly encode letter position information (Vidyasagar & Pammer, 2010; Whitney & Cornelissen, 2005). By comparing results from the dyslexic children to the correct samples of typically developing children, these issues can be addressed. To this end, the current study explored parafoveal processing of orthographic information for children with dyslexia compared to both chronological age and reading age matched control groups.

It is important to explore the trajectory of deficits in developmental dyslexia. By using reading age and chronological age matched control groups one can examine to what extent the deficits demonstrated by dyslexic readers are explained by their reading difficulties (therefore representing deficits that occur due to a reading delay), or are due to specific cognitive deficits related to dyslexia. Such results will help to inform whether the differences found within adult dyslexic orthographic parafoveal processing are attributable to their poor reading skills, or a function of a specific dyslexic deficit. Studies of foveal processing have shown that dyslexic readers have different patterns of eye movements during reading compared to typically developing children matched for chronological age; longer and more fixations, shorter saccades, longer total reading times, more regressions and landing positions that occur earlier within a word (for a reviews, see Kirkby et al., 2011; Bellocchi et al., 2013). However, these eye movement patterns are largely believed to reflect their difficulty with linguistic processing, and there are a small number of studies that suggest dyslexic eye movement patterns are indeed similar to typically developing children matched for reading age (Hyönä & Olson, 1995; Rayner, 1985a, Rayner 1985b). There is, however, a lack of research specifically aimed at exploring the eye movement patterns for dyslexic children in comparison to reading age matched children during foveal and parafoveal processing.

Similar to Experiment 1 with dyslexic adult readers (reported in Chapter 3), the current study used identical previews (IP; e.g. *caught*), transposed-letter previews (TL; e.g. *acught*), and substituted-letter previews (SL; e.g. *erught*) during the boundary paradigm to explore orthographic parafoveal processing. Again, manipulations occurred within the initial letter of the parafoveal word; recall that whilst TL effects may be somewhat reduced within the initial letters of the parafoveal word (discussed in detail in Chapter 3) they were selected for the following reasons: 1) dyslexic readers and children more generally have both been found to have a reduced perceptual span compared to skilled reading adults (Blythe, 2014; Blythe & Joseph, 2011; Rayner et al., 2013; Rayner et al., 1989), in which case their parafoveal processing may be limited to the beginning of the parafoveal word, 2) as discussed in Chapter 3, the initial letters of a word may be more important due to sequential mapping of phonological information, in which case transposing the initial letters of a word may in fact heighten the disruption caused to readers with dyslexia due to dyslexic readers' difficulty with mapping phonology to orthography (Liberman, 1973; Snowling, 1995; Snowling, 2000; Snowling & Hulme, 2012; Stanovich, 1988). Indeed, similarly to skilled adults, typically developing children show greatest disruption to lexical activation when the initial letters of a word are transposed compared to internal letters of a word (Pagán et al., 2016; Tiffin-Richards & Schroeder, 2015).

The current study aimed to address the following questions; 1) Do children with dyslexia encode letter position information within the parafovea during reading? 2) Do children with dyslexia encode letter position information flexibly within the parafovea, thus demonstrating the TL effect? 3) Do children with dyslexia show orthographic parafoveal processing abilities similar to those of typically developing children matched for reading age matched or chronological age? 4) Do children with dyslexia show foveal eye movement patterns that are similar to those of typically developing children matched for reading or chronological age?

Based on studies reviewed above and in Chapter 1, it was predicted that children with dyslexia would show foveal eye movement patterns indicative of their reading difficulties compared to typically developing children matched for chronological age (i.e. longer fixation durations, more fixations etc.). However, as typically developing children matched for reading age and dyslexic children have similar reading abilities, it was predicted that dyslexic readers would show similar foveal eye movement patterns to the reading age matched children.

Based on the findings of Pagán et al. (2016), it was predicted that typically developing children would show orthographic parafoveal preview benefits during reading, whereby they gain benefit of identical previews compared to transposed-letter previews, and, transposed-letter previews compared to substituted letter previews. Whilst it was predicted that both typically developing child groups would show such orthographic preview effects, it is also possible that the typically developing children matched for reading age show a slightly different pattern of parafoveal processing compared to the older children, as it is currently unclear exactly how reading age and chronological age impact the development of parafoveal processing. Indeed, similarly to findings of TL effects in children (Acha & Perea, 2008; Castles et al., 2007; Lété & Fayol, 2013), younger children might demonstrate more flexible encoding of letter position.

Furthermore, from the findings presented in Chapter 3 that report parafoveal processing in adult dyslexic readers and the results of Yan et al. (2013) who found dyslexic parafoveal processing for children during RAN, it was predicted that dyslexic children would show parafoveal preview benefits during reading. In addition, further to Chapter 3, in which dyslexic adults and skilled reading adults showed differences in flexible letter position encoding during parafoveal processing, we predicted differences between the parafoveal processing abilities of dyslexic readers and typically developing children matched for chronological-age. Whilst we found difference in letter position encoding for adults with dyslexia compared to skilled adult readers, for children with dyslexia, we might find a slightly different pattern of results. As, children are still developing their reading skills, deficits in letter position encoding may manifest differently compared to dyslexic adults. In line with Vidyasagar and Pammer (2010), and, Whitney and Cornelissen (2005), dyslexic children may have specific deficits in attention allocation, which make it difficult to encode letter position, in which case dyslexic children would show an equal benefit of identical previews and transposed-letter previews. However, it is also possible, that similarly to dyslexic adults, children with dyslexia show less flexibility within their letter position encoding; this would result in a pattern of results where transposed-letter previews provide similar parafoveal preview benefits to substituted-letter previews (a reduced TL effect).

Finally, whilst we predicted differences in parafoveal processing between dyslexic and typically developing children matched for chronological age, predictions for comparisons between dyslexic and reading age matched typically developing children are more speculative. Indeed, dyslexic children might develop their parafoveal processing skills alongside their reading ability, in which case they would demonstrate parafoveal processing abilities similar to that of reading age matched children. However, if children with dyslexia have an attentional deficit that impacts their ability to parafoveally process information during reading that occurs independently of their poor reading skills, then dyslexic children and children matched for reading age will show different patterns of parafoveal processing.

4.2 Method

4.2.1 Participants

Participants were 18 children with developmental dyslexia (mean age of 10 years 4 months and reading age of 8 years 0 months), 28 typically developing children with a similar chronological age (CA) as the dyslexic readers (mean age of 10 years 2 months and reading age of 12 years 7 months) and 28 typically developing children with a similar reading age (RA) as the dyslexic children (mean age of 8 years 8 month and reading age of 8 years 3 months). Children with dyslexia had a prior, independent diagnosis of dyslexia, through their local education authority. All participants were native English speakers with normal or corrected to normal vision and were recruited from local schools. The children performed within or above the normal range for IQ (IQ≥90; Wechsler, 1999). To ensure the child groups were well matched, two one-way ANOVAs were conducted to examine chronological age and then reading age across the three groups. There was a significant difference in the chronological age of the three groups, $F(2,73) = 47.66$, $p < .001$. The reading age matched children were significantly younger than both the children with dyslexia and the age matched children (*p's*< .001); there was no difference in the age of the children with dyslexia and the chronological age matched children. There was also a significant difference in reading age, $F(2,73) = 48.08$, $p < .001$; the chronological age matched children had a significantly higher reading age than both children with dyslexia and the reading age matched children (*p's*< .001). The children with dyslexia and the reading age matched children, however, did not differ significantly on reading age.

4.2.2 Apparatus

Eye movements were recorded from the right eye using a SR Research Eyelink 1000 eye-tracker. Sentences were presented at a viewing distance of 660 mm on a 21 inch Formac ProNitron 21/750 monitor with a screen resolution of 1024 x 768 pixels and a refresh rate of 120 Hz. Sentences were presented in black 14pt Courier New font on a white background.

4.2.3 Design and stimuli

Three parafoveal preview conditions were presented using the boundary paradigm (Rayner, 1975). Parafoveal previews of the target words were either 1) identical to the target word (IP), 2) a transposed-letter non-word (TL), or 3) a substituted-letter non-word (SL). The manipulation occurred in the initial two letters of the target word, both to examine the impact of parafoveal processing for initial letters (which may in fact have a specific importance related to phonological processing) and also because these letters are indeed spatially closer to foveal vision and dyslexic readers may have reduced perceptual span (Rayner et al., 1989). For the transposed-letter conditions, the positions of the two initial letters were switched and for the substituted-letter conditions, the initial two letters were replaced with visually similar letters (ascenders were replaced with ascenders and descenders with descenders) to retain orthographic similarity. Target words were always 6 letter words and were preceded by a 5 letter pre-target word to increase the likelihood of a children fixating upon both the words. Pre-target and target words were presented towards to the middle of the sentence and were high frequency words. High frequency words were chosen in attempt to reduce foveal load and allow for parafoveal processing. The mean frequency of the pre-target word was 618 counts per million and the mean frequency of the target word was 409 counts per million. Frequency counts were taken from the Children's Printed Word Database (CPWD; Masterson, Stuart, Dixon, & Lovejoy, 2010) as this best reflects frequency counts for children; indeed word frequency for children can differ to that found for adults. Sentences were single line sentences ranging from 9-12 words (45-60 characters).

The stimuli consisted of 60 sentence frames and for each sentence frame there were 3 versions corresponding to the three parafoveal preview conditions (See Table 4.1 for an example). Three experimental lists were constructed whereby each list contained a different version of each sentence frame and the parafoveal preview manipulations were randomised across the 3 experimental lists so each participant saw 20 sentences from each of the three preview conditions.

The eye movement contingent change boundary was located at the end of the pre-target word and to the left of the space preceding the target word. When the eyes moved past the invisible boundary, the target word changed from the parafoveal preview to the target word. The correct target word then remained in the sentence throughout the remaining duration of the trial. Display changes were typically undetected by the readers as they occurred during a saccade (when visual information is suppressed). Indeed when participants were questioned whether they noticed anything unusual during the experiment, very few reported noticing anything and those who did notice something suggested it occurred in a very small number of trials (less than 4 trials) and were unable to explain what had happened.

Table 4.1. Examples of the target word manipulation. Sentence frames included either an identical preview (IP), a transposed-letter non-word preview (TL), or a substituted-letter non-word preview (SL).

	Example sentence
Identical	The group of boys never *caught* any frogs at the pond.
Transposed	The group of boys never *acught* any frogs at the pond.
Substituted	The group of boys never *erught* any frogs at the pond.

4.2.4 Offline measures of reading ability and IQ

As discussed in Chapter 2, offline tests were conducted in order to establish that our groups of readers showed patterns representative of their reading group and to gain further understanding of their general intelligence and reading profiles. As such, all participants completed a range of offline tests. IQ was measured using two subtests of the Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler, 1999); i) the vocabulary subtest, ii) the matrix reasoning subtest (for the full details on the WASI IQ test, refer back to Chapter 2).

Whilst the TOWRE was used within Experiment 1 to examine reading ability of adult participant (detailed in Chapter 3), the TOWRE is not well suited to child participants. For this reason, the current experiment used the Word Reading and Pseudoword Reading subtests of the Wechsler Individual Achievement Test – Second Edition (WIAT-II; Wechsler, 2005) as an equivalent for children. Similarly to the TOWRE, these subtests were used to record sight word reading using a list of real words and the phonemic decoding using a list of pseudowords. However, unlike the TOWRE, children were not provided a time limit, they continued to read the list until they either completed all items or consistently made errors and therefore were asked to stop reading. The Word Reading and Pseudoword Reading subtests provided standardised measures of reading ability based upon a child's chronological age. Thus, in the instance of dyslexic readers, they show a standardised score that represents their low reading skills relative to their chronological age. The result from the Word Reading subtest were used to determine each child's reading age, whereby the raw score taken from Word Reading indicates at what age-level a child is reading. As such, reading age was used as a comparative measure across all children regardless of their chronological age.

All children also completed the Number and Letters measures of the Rapid Automatised Naming (RAN; Wolf & Denckla, 2005) test in which they were required to read an array of letters or numbers presented within rows, as quickly and correctly as possible (again see Chapter 2 for discussion of the use of RAN as an offline measure). The time taken to correctly read aloud the items provides the RAN score which is then standardised across age and used an indication of how well individuals can integrate both visual and language information. Finally, all children completed a phoneme deletion task (McDougall et al., 1994). The phoneme deletion task is an additional measure of phonological awareness, which does not require oral reading, and was used to provide further support for the reading tests. Within this 24 item task, children were told a word and asked what word would remain if a given phoneme were deleted from the word. As there are no standardised scores for this test, results are scored based on the number of correct answers.

4.2.5 Procedure

Participants sat in front of a computer screen with their head positioned in a forehead and chin rest to minimise head movements. They were instructed to read the sentences silently for comprehension and to press a button on a gamepad once they had finished reading. A 3-point calibration was conducted prior to the experimental trials and selected due to the horizontal nature of single line sentences; an accurate calibration was accepted when the average errors in the validation were below 0.3° of visual angle. Calibrations were confirmed throughout the experiment and repeated when required. Each trial began with a gaze contingent box (a small black square) presented on the left hand side of the screen, positioned so that the initial letter of the sentence occupied the same location. Once the participant had fixated the square for 250ms, the sentence appeared on the screen. Participants then read the sentence silently and terminated the trial with a button press. After 25% of the experimental sentences a “yes/ no” comprehension question appeared; participants were required to press a corresponding button to answer the question.

4.2.6 Statistical analysis

Prior to the analysis, fixations less than 80ms were either merged into nearby longer fixations or excluded and fixations more than 800ms were excluded from the data set (5.49% of fixations). Additional trials were excluded based upon the following criteria; 1) when the boundary was triggered prior to a saccade being made across the boundary, 2) when the display change completed more than 10ms after a fixation landing on the target word, 3) when the end of a saccade briefly crossed the boundary but the successive fixation remained in a position before the boundary, 4) when participants blinked on either the pre-target or target word, 5) when the participants skipped either the pre-target or target word. In total 1,522 trials were removed from the analyses (34% of the dataset), data were excluded similarly across groups and conditions.

4. 3 Results

As discussed in Chapter 2, analyses were conducted for both global and local eye movement measures. Global measures refer to results from all of the fixations within the sentence whereas local measures were based solely on the eye movements that occurred on the target word. Data were analysed using linear mixed models (LMMs; see Chapter 2 for further discussion on the use of LMMs) using the lme4 package (version 1.1.12) in R (version 3.3.1). For global analysis, reading group was used as the fixed factor for all models. For local analysis both reading group and preview condition were fixed factors for all models. Participants and items were specified as random effects. For each dependent measure, a "full" random structure was implemented including all varying intercepts and slopes of the main effects and their interaction (maximal random effects structure as suggested by Barr et al., 2013). If the "full" model failed to converge, or there were too many parameters to fit the data (as indicated by correlations of 0.99, 1, -0.99 or -1 in the random structure), the random structure was systematically trimmed (first by removing correlations between random effects, and if necessary also by removing their interactions). Successive difference contrasts were used for preview condition (comparing IP and TL, followed by TL and SL). Orthogonal contrasts were used for reading group with the first contrast exploring chronological age matched children compared to dyslexic and reading age matched children, and the second contrast exploring dyslexic children compared to reading age matched children. For each contrast we report beta values (b), standard error (SE) and t or z statistics. Fixation time analyses were carried out on log-transformed models to increase normality and count data were analysed using generalised linear mixed models following a Poisson distribution (GLMMs).

4.3.1 Eye tracking comprehension questions

The mean accuracy in comprehension score was 87.78% correct for dyslexic children, 91.43% for chronological age matched children and 88.57% for reading age matched children. There was no significant difference between the comprehension scores for the three groups, $F\,(2,71) = 1.34$, $p = .27$, suggesting all reading groups were able to read these sentences well enough to correctly respond to the comprehension questions.

4.3.2 Off-line measures of reading ability and IQ

Mean scores for all offline tests are presented in Table 4.2. ANOVAs were conducted to explore the differences between reading groups across the offline measures. There was a significant main effect for Word Reading ($F\,(2,71)$, 25.37, p

<.001) and Pseudoword Reading (*F* (2,71), 15.10, *p* <.001). As both of these measures are presented as standardised scores based upon chronological age, dyslexic children performed significantly lower compared to the both groups of typically developing children (*p's* <.001). Although there were no significant differences between the three reading groups for the letter subset of the RAN (*F* (2,71), 1.52, *p* =.225), there was a significant effect for the number subset of the RAN (*F* (2,71), 5.80, *p* =.005); children with dyslexia performed significantly slower than the age matched children (*p*=.015) and reading age matched children (*p*=.007). Again there was a significant difference in the scores on the phoneme deletion task (*F* (2,71), 5.88, *p* =.004), with both dyslexic readers and reading age matched children performing significantly poorer than chronological age matched children (*p*<.001). There was, however, no difference in the phoneme deletion scores for dyslexic and reading age matched children (*p*>.05)

Table 4.2. Mean scores for the offline tests and age data for children with dyslexia, reading age matched children and chronological age matched children. Standard scores are provided for Word Reading, Pseudoword Reading and RAN numbers and letters, and, IQ. Standard deviations are shown in parentheses.

	Dyslexic Children	Reading Age Matched Group	Chronological Age Matched Group
Chronological Age	10 years 4 months	8 years 8 months	10 years 2 months
Reading Age	8 years 0 months	8 years 3 months	12 years 7 months
Word reading	84.33 (9.65)	102.54 (11.46)	108.25 (12.12)
Pseudoword reading	88.17 (10.30)	103.54 (14)	108.57 (12.16)
RAN letters	94.54 (12.12)	99.89 (15.95)	101.72 (12.54)
RAN numbers	95.00 (10.68)	106.56 (11.69)	105.28 (12.35)
Phoneme Deletion	12.44 (3.77)	14.41 (4.17)	18.63 (1.79)
IQ	101 (10)	111 (14)	113 (10)

4.3.3 Global measures

Similarly to those reported in Experiment 1 (Chapter 3), the following global measures were included; total sentence reading time, average saccade amplitude, average forward and regressive fixation duration, and total number of forward and regressive fixations per sentence (See Table 4.3 for means and Table 4.4 and Table 4.5 for model outputs). Forward and regressive fixations were classified based upon the previous saccade direction (fixations preceded by a rightward saccade are considered forward fixations and fixations preceded by a leftward saccade are referred to as regressive fixations). Global measures allowed for exploration of the differences between reading groups at a sentence level.

Total reading time: As predicted, dyslexic readers and reading age matched children had significantly longer total reading times compared to those of the chronological age matched children, thus demonstrating their difficulties with linguistic processing relative to the chronological age matched children. There was also a marginally significant difference in the total reading times of the children with dyslexia compared to reading age matched children, whereby dyslexic children had longer total reading times than the reading age matched children; suggesting dyslexic eye movement patterns may not solely be explained by their reduced reading skills.

Saccade amplitude: Dyslexic readers and reading age matched children had shorter saccade amplitudes compared to those made by the chronological age matched children. In addition, there were no differences between the saccade amplitudes of dyslexic children and reading age matched children.

Forward and regressive fixation durations: For both forward and regressive fixation durations, dyslexic readers and reading age matched children made longer fixations compared to the fixations made by the chronological age matched children, again indicating their linguistic processing difficulty relative to the chronological age matched children. For forward fixation duration, there was no difference in the duration of fixations for the dyslexic children compared to reading age matched children. For regressive fixation duration, however, there was a significant difference between the dyslexic children and the reading age matched children; dyslexic readers made longer regressive fixations, indicating that even when matched on reading age, dyslexic readers show a specific requirement for longer regressive fixation durations compared to non-dyslexic readers.

Forward and regressive fixation counts: Dyslexic readers and reading age matched children made more forward and regressive fixations compared to the number of fixations made by chronological age matched children. There were no significant differences between the number of fixations made for the dyslexic children and the reading age matched children, for either forward or regressive fixations.

Table 4.3. Average global reading measures. Total reading time (ms), saccade amplitude (degrees), average fixation duration (ms) and number of fixations, for children with dyslexia, typically developing children matched for reading age and typically developing children matched for chronological age.

	Total Time		Saccade Amplitude		Fixation Duration				Fixation Count			
					Forward		Regressive		Forward		Regressive	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
Dyslexic children	7120	3171	1.93	0.59	288	46	293	73	13.06	4.29	4.87	2.93
Reading age match	6350	2883	2.01	0.62	282	50	277	77	12.75	4.23	4.25	2.78
Chronological age match	4374	1843	2.26	0.57	245	40	251	85	10.79	3.32	3.40	2.79

Table 4.4. Model output for LMMs conducted for global reading measures of total reading time (ms), saccade amplitude (degrees), average forward fixation duration (ms) and average regressive fixation duration. Significant t values (≥ 1.96 of standard error, SE) are marked in **bold**.

	Total Time			Average saccade amplitude			Forward fixation duration			Regressive fixation duration		
	b	SE	*t*	*b*	SE	*t*	*b*	SE	*t*	*b*	SE	*t*
Intercept	8.61	0.04	**229.52**	0.67	0.02	**29.50**	5.59	0.01	**397.47**	5.57	0.01	**433.39**
DR + RA vs CA	-0.43	0.07	**-5.85**	0.16	0.05	**3.57**	-1.61	0.03	**-5.67**	-0.15	0.03	**-5.72**
DR vs RA	0.16	0.09	1.77	-0.08	0.06	-1.44	0.02	0.04	0.59	0.06	0.03	**1.97**

Table 4.5. Model output for GLMMs conducted for global reading measures of forward fixation count and regressive fixation count. Significant z values (≥ 1.96 of standard error, SE) are marked in **bold.**

	Forward fixation count			Regressive fixation count		
	b	SE	*z*	*b*	SE	*z*
Intercept	2.49	.03	**98.80**	1.34	0.06	**24.31**
DR + RA vs CA	-0.18	0.05	**-3.88**	-0.37	0.11	**-3.44**
DR vs RA	0.06	0.06	1.03	0.17	0.13	1.26

4.3.4 Local measures

The following measures were analyzed for the embedded target words; first fixation duration, single fixation duration, gaze duration, go-past time, total reading time, fixation count and landing position. First fixation duration is the duration of the initial fixation on the target word. Single fixation duration represents those fixations for which the reader made only one fixation on the target word during first pass. Gaze duration is the sum of fixation durations on the target word before the reader leaves that word. Go-past time is the sum of fixations durations on the target word from when a reader first fixated that word until their first fixation to the right of that word (including any regressions made before moving forward past the target word). Total time is the sum of all fixations that occur on the word throughout the whole trial (including any regressive fixations). Landing position is the character location of which the eye fixates. Table 4.6 provides the mean results for first fixation duration, single fixation duration, gaze duration, total reading time and fixation count across reading group and preview condition. Table 4.7 provides the LMM outputs and Table 4.8 provides LMM outputs for the simple effects analysis for when interactions between group and preview occurred.

First fixation duration: For first fixation duration there was a main effect of group in the predicted direction; dyslexic children and reading age matched children required longer first fixation durations than chronological age matched children. The were no significant differences between the first fixation durations of children with dyslexia and typically developing children matched for reading age, indicating they make first fixations of a similar duration. The main effects for both preview condition contrasts were not significant but there was a significant interaction in which shorter first fixation durations were made on identical previews than transposed-letter previews, however, this effect only occurred for the chronological age matched children. Thus, for single fixation duration, only the chronological age matched children showed any benefit of parafoveal information during reading and this preview benefit demonstrated that chronological age matched children do in fact encode letter position from the parafovea. All other interactions did not reach significance.

Single fixation duration: In single fixation duration, there was a similar pattern to that of first fixation duration. Dyslexic children and reading age matched children required longer single fixation durations than chronological age matched children, again, indicating their linguistic processing difficulties in comparison to the chronological age matched children Again, there was no significant difference between the single fixation durations of the children with dyslexia and reading age matched children. The main effect comparing identical previews and transposed-letter previews showed no significant difference in single fixation duration, however, there was an interaction in which shorter single fixation durations were made on identical previews than transposed-letter previews specifically for the chronological age matched children. This result provides further evidence of parafoveal preview benefit and letter position encoding in chronological age matched children. There was also a significant main effect whereby shorter single fixations were made for transposed-letter previews than substituted-letter previews, suggesting all reading groups encode letter identity during single fixation duration. The additional interactions were not significant.

Gaze duration: As predicted, dyslexic children and reading age matched children required longer gaze durations compared to chronological age matched children. In addition, dyslexic children required longer gaze durations than reading age matched children, indicating that dyslexic readers' reduced reading age (compared to their peers) is not the sole cause for their increased gaze durations and there is something specific to dyslexic readers that means they require increased gaze durations compared to non-dyslexic readers. For the preview condition contrasts, both main effects were significant; shorter gaze durations were made on identical previews compared to transposed-letter previews, and, transposed-letter previews compared to substituted-letter previews. None of the interactions were significant (see Figure 4.1). However, in order to confirm our hypothesis, a simple effects analysis was conducted to explore the TL effect for dyslexic readers. The simple effects analysis indicated shorter gaze durations were made upon transposed-letter previews compared to the substituted-letter previews for the dyslexic children, indicating that the TL effect occurs in children with dyslexia. In fact, all reading groups showed evidence of parafoveal processing during reading, specifically, all groups were able to encode letter position and encode letter position independently to letter identity (the TL effect).

Go-past time: Similarly to previous measures, dyslexic children and reading age matched children required longer go-past times than chronological age matched children. Moreover, dyslexic children required longer go-past times than reading age matched children, providing further evidence that dyslexic readers' reduced reading age (compared to their peers) cannot fully account for the eye movement patterns of readers with dyslexia. Similarly to gaze duration, there was also evidence for main effects for both preview condition contrasts; shorter gaze durations were made on identical previews compared to transposed-letter previews, and, transposed-letter previews compared to substituted-letter previews. There was, however, a marginally significant interaction to suggest that dyslexic readers do, in fact, show a greater benefit of transposed-letter previews compared to substituted-letter previews than children matched for reading age. Indeed, a simple effects analysis indicated shorter gaze durations were made upon transposed-letter previews compared to the substituted-letter previews for the dyslexic children, thus providing further evidence of a TL effect in children with dyslexia.

Total reading time: Similarly to gaze duration, dyslexic children and reading age matched children required longer total reading times than chronological age matched children, and, dyslexic children required even longer total reading times than reading age matched children. For the effects of preview, there was only a significant main effect in which total reading times were longer for transposed-letter preview compared to substituted-letter previews. The main effect comparing identical previews to transposed-letter previews was not significant and none of the interactions were significant. Again, simple effects analysis was conducted to determine if the TL effect occurred in dyslexic readers. Similarly to that found for gaze duration, dyslexic readers had shorter total reading times on transposed-letter previews than substituted-letter previews, thus, proving further support for flexible letter position encoding for readers with dyslexia.

Landing position: Whilst dyslexic readers show a numerical trend to support earlier landing positions compared to both chronological and reading age matched children, none of the group effects were significant. Furthermore, there were no effects of preview condition on landing position and none of the interactions were significant.

Fixation count: Dyslexic children and reading age matched children required more fixations than chronological age matched children. In addition, dyslexic children required more fixations compared to reading age matched children, further indicating that dyslexic readers demonstrate specific reading difficulties that are not explained by their reduced reading age. There were, however, no significant effects for either preview contrast and no evidence to support any of the interactions.

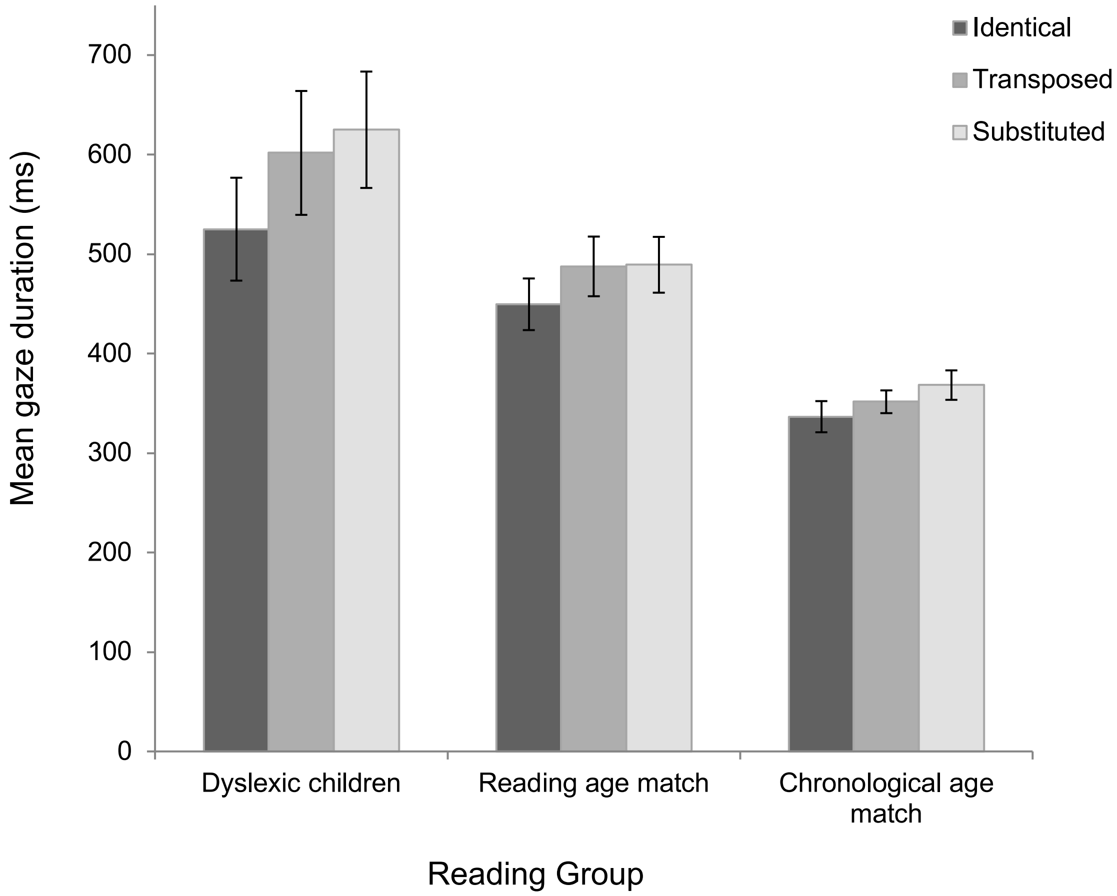

Figure 4.1. Mean gaze durations for dyslexic children, reading age matched typically developing children, and chronological age matched typically developing children across identical previews, transposed-letter previews and substituted-letter previews. Error bars show standard error in each preview condition.

Table 4.6. Mean first fixation duration, single fixation duration, gaze duration, go-past time, total reading time, fixation count and landing position for the target word, as a function of preview condition and reading group.

	Identical Preview	Transposed	Substituted
First fixation duration (ms)			
Dyslexic	322 (138)	319 (132)	320 (131)
Reading age match	312 (128)	305 (134)	323 (137)
Chronological age match	252 (93)	270 (98)	276 (100)
Single fixation duration (ms)			
Dyslexic	352 (137)	341 (127)	371 (137)
Reading age match	325 (122)	329 (135)	358 (131)
Chronological age match	265 (96)	288 (103)	301 (105)
Gaze duration (ms)			
Dyslexic	515 (354)	579 (451)	588 (402)
Reading age match	455 (269)	497 (309)	486 (262)
Chronological age match	342 (189)	353 (154)	371 (162)
Go-past time (ms)			
Dyslexic	753 (876)	741 (653)	807 (584)
Reading age match	634 (622)	700 (614)	655 (490)
Chronological age match	436 (379)	484 (424)	480 (438)
Total time (ms)			
Dyslexic	782 (557)	772 (559)	803 (585)
Reading age match	650 (421)	687 (448)	700 (426)
Chronological age match	467 (298)	491 (290)	495 (289)

Table 4.6 continued.

	Identical Preview	Transposed	Substituted
Fixation count			
Dyslexic	2.60 (1.84)	2.55 (1.76)	2.69 (1.87)
Reading age match	2.20 (1.33)	2.36 (1.45)	2.40 (1.47)
Chronological age match	1.90 (1.09)	1.95 (1.12)	1.94 (1.13)
Landing position			
Dyslexic	2.84 (1.43)	2.90 (1.51)	2.84 (1.46)
Reading age match	3.08 (1.62)	3.05 (1.59)	3.01 (1.57)
Chronological age match	3.09 (1.62)	3.10 (1.55)	3.08 (1.52)

Table 4.7. Model output for LMMs conducted for local reading measures of first fixation duration (ms), single fixation duration (ms), gaze duration (ms), go-past time (ms) total reading time (ms), fixation count and landing position (characters). Significant t or z values (≥ 1.96 of standard error, SE) are marked in **bold**.

	First fixation			Single fixation			Gaze duration			Go-past time		
	b	SE	*t*	*b*	SE	*t*	*b*	SE	*t*	*b*	SE	*t*
Intercept	5.62	1.72	**327.25**	5.71	2.29	**249.23**	6.00	0.03	**190.78**	6.22	0.04	**173.36**
IP vs TL	1.07	1.79	0.60	1.74	2.56	0.68	0.07	0.02	**3.39**	0.10	0.03	**2.86**
TL vs SL	2.41	1.92	1.26	7.23	2.65	**2.73**	0.06	0.02	**2.70**	0.06	0.02	**2.04**
DR + RA vs CA	-1.62	3.41	**-4.75**	-1.94	4.35	**-4.459**	-0.34	0.06	**-5.74**	-0.40	0.07	**-6.06**
DR vs RA	2.81	4.31	0.65	2.02	5.60	0.36	0.16	0.07	**2.16**	0.18	0.08	**2.11**
IP vs TL: DR + RA vs CA	8.75	3.54	**2.47**	9.63	4.44	**2.17**	-0.02	0.04	-0.48	0.07	0.07	1.20
TL vs SL: DR + RA vs CA	-7.86	3.39	-0.23	-3.63	4.17	-0.87	-0.01	0.04	-0.03	-0.09	0.05	-1.65
IP vs TL: DR vs RA	1.11	4.51	0.25	-5.57	5.99	-0.93	-0.02	0.05	-0.30	-0.06	0.08	-0.80
TL vs SL: DR vs RA	-5.15	4.36	-1.18	-5.44	5.87	-0.001	0.07	0.05	1.28	0.12	0.07	1.79

Table 4.7 continued.

	Total time			Fixation count			Landing position		
	b	SE	*t*	*b*	SE	*t*	*b*	SE	*t*
Intercept	6.31	0.04	**179.79**	0.81	0.03	**25.51**	2.98	0.06	**52.34**
IP vs TL	0.04	0.02	1.46	0.02	0.03	0.72	0.01	0.08	0.18
TL vs SL	0.05	0.02	**2.17**	0.03	0.03	1.02	-0.04	0.08	-0.47
DR + RA vs CA	-0.34	0.06	**-6.26**	-0.25	0.06	**-4.12**	0.16	0.11	1.50
DR vs RA	0.16	0.08	**2.00**	0.15	0.07	**2.04**	-0.21	0.14	-1.55
IP vs TL: DR + RA vs CA	0.06	0.05	1.22	0.01	0.07	0.13	-0.01	0.14	-0.05
TL vs SL: DR + RA vs CA	-0.05	0.05	-0.97	-0.05	0.06	-0.82	0.01	0.14	0.03
IP vs TL: DR vs RA	-0.08	0.06	-1.19	-0.08	0.08	-1.01	0.10	0.18	0.54
TL vs SL: DR vs RA	0.04	0.06	0.74	0.05	0.08	0.61	-0.02	0.19	-0.09

Table 4.8. LMM output for simple effects analysis exploring TL compared to SL for dyslexic readers in measures of gaze duration (ms), go-past time (ms) and total reading time (ms). Significant t values (≥ 1.96 of standard error, SE) are marked in **bold**.

	Gaze duration			Go-past time			Total time		
	b	SE	*t*	*b*	SE	*t*	*b*	SE	*t*
Intercept	5.97	0.04	**168.47**	6.22	0.04	**153.62**	6.30	0.04	**158.00**
TL vs SL	-0.10	0.04	**-2.35**	-0.18	0.05	**-3.40**	-0.11	0.05	**-2.40**

4.4 Discussion

The aim of the current study was to examine whether children with dyslexia gain orthographic parafoveal preview benefit during reading. Specifically, to determine whether dyslexic children encode letter position information from the parafovea, and if letter position is encoded parafoveally, to explore whether it is encoded independently to letter identity. In addition, the current study examined whether dyslexic children show foveal and parafoveal eye movement patterns that are similar to typically developing children matched for chronological age or to typically developing children matched for reading age.

The pattern of results presented in this chapter indicated that all reading groups gained parafoveal preview benefit from orthographic information. All reading groups, including readers with dyslexia, showed a preview benefit (i.e. subsequent reading times were shorter when the target was fixated) when an identical parafoveal preview was presented compared to when a transposed-letter preview was presented, indicating that letter position was encoded from the parafovea. Furthermore, all reading groups were found to benefit from transposed-letter previews more than previews containing substituted-letters, thus demonstrating that letter identity was encoded independently to letter position during parafoveal processing. For typically developing children matched for chronological age (the most skilled reading group tested within this sample), these preview effects occurred within early measures of reading such as first fixation duration and single fixation duration. However, for readers with dyslexia and reading age matched children, the effects only occurred within later measures such as gaze duration, go-past time and total reading time. These findings indicate that that reading age impacts the time point at which parafoveal preview effects occur in eye movement measures during reading, due to more efficient lexical processing that occurs alongside reading development (Reichle et al., 2013). Furthermore, such finding demonstrates that parafoveal processing occurs similarly for dyslexic readers and children matched for reading age. Indeed, the only significant difference between the parafoveal preview benefits of dyslexic children and typically developing children matched for reading age, occurred within go-past time where readers with dyslexia showed a larger TL effect than was found for reading age matched children. Dyslexic readers, however, showed a numerical trend indicating that they did not gain a preview benefit of identical previews compared to transposed-letter previews, thus indicating that dyslexic readers were less able to encode letter position information during go past time compared to reading age matched children. Furthermore, children with dyslexia and reading age matched children showed foveal eye movement patterns indicative of their reading skill and reduced lexical processing efficiency; longer fixation durations, more fixations, shorter saccades, longer total reading times compared to the chronological age matched children. There were, however, also a number of differences between the eye movement patterns of children with dyslexia and reading age matched children; these differences occurred within later measures where dyslexic children showed longer gaze durations and total reading times than reading age matched children.

Similarly to previous research on children's parafoveal processing (Häikiö et al., 2010; Marx et al., 2015; Pagán et al., 2016; Tiffin-Richards & Schroeder, 2015), the current findings provided evidence for parafoveal preview benefit in typically developing children. In the current study, orthographic parafoveal processing abilities were explored in a range of ages and reading abilities. In line with the findings of Pagán et al. (2016), who found orthographic parafoveal processing abilities for 8 year old children, the current results also provided evidence that children as young as 8 years old demonstrated benefit from orthographic parafoveal information and were able to parafoveally encode letter identity independently to letter position (thus demonstrating the TL effect during parafoveal processing). What is particularly interesting within the current study, however, is that the 8 year old sample of typically developing children (selected to have a reading age to match the dyslexic children) did, in fact, have a reading age representative of their chronological age (8 years old). This is in contrast to Pagán et al. (2016), who had a sample of 8 year old children with a mean reading age of 11 years old. The current findings, therefore, suggest that children with a reading age as young as 8 years old do in fact demonstrate TL effects during parafoveal processing.

In addition to the 8 year old reading age matched children included within the current study, the 10 year old typically developing children matched for chronological age also demonstrated the TL effect during parafoveal processing. In fact, the only difference in orthographic parafoveal processing abilities of 8 year old typically developing children and 10 year old typically developing children tested within the current study, was the eye movement measures in which the effects occurred. For the 10 years olds, orthographic preview effects were demonstrated in measures of first fixation duration and single fixation duration as well as gaze duration, go-past time and total reading time. In contrast, the 8 year old reading age matched children showed effects of orthographic preview benefits only in later measures of gaze duration, go-past time and total time. This demonstrates that children with a younger age and reading age show orthographic preview effects at a delayed time frame compared to older, more skilled child readers. This is in line with a developmental increase in the rate of lexical processing (Reichle et al., 2013) and the findings that lexical processing is slower in children compared to adults (e.g., Blythe, 2014; Blythe et al., 2006, 2009, 2011; Häikiö et al., 2009, 2010; Huestegge et al., 2009; Joseph et al., 2009; McConkie et al., 1991; Rayner, 1986; Reichle et al., 2013; Tiffin-Richards & Schroeder, 2015).

The fact that 8 year old typically developing children demonstrated a TL effect during parafoveal processing (specifically in later eye movement measures) differs to the results of Tiffin-Richards and Schroeder (2015) who only found evidence of orthographic parafoveal processing in single fixation duration for German readers aged 8 years old. However, as they noted, single fixation is a particularly unreliable measure for young readers due to their increased likelihood of refixating a word. As such, Tiffin-Richards and Schroeder (2015) suggest that German children depend more so upon phonological parafoveal processing whereas adults rely upon orthographic parafoveal processing. As the current study provides support for orthographic parafoveal processing in young English readers, it is possible that orthographic depth plays a role in the development of parafoveal processing. As discussed, German is a less opaque orthography than English; therefore, it is possible that English readers have a greater reliance on orthographic information during reading development.

Further to the discussion of orthographic parafoveal processing in typically developing children, and specifically to the aim of this thesis, the current study explored orthographic parafoveal processing for dyslexic children. In line with Yan et al. (2013), who explored parafoveal processing during RAN, and the results for adult dyslexic readers reported in Chapter 3 of this thesis, the current pattern of results provide evidence that dyslexic children gain parafoveal preview benefit during reading. Evidence was provided to show that dyslexic readers aged 10 years old with a reading age of 8 years old could also encode letter identity and letter position from the parafovea. Furthermore, evidence suggests that similarly to the results found for adults with dyslexia (reported in Chapter 3), dyslexic children can also encode letter identity and letter position independently; in fact, dyslexic children showed a preview benefit for transposed-letter previews compared to substituted-letter previews in gaze duration, go-past time and total reading time. Such results are contrary to our predictions, and to those proposed by Whitney and Cornelissen (2005) who suggested dyslexic readers have specific deficit in attention allocation, which impacts on their ability to encode letter position. As such, the current results provide evidence to suggest that children with dyslexia are in fact able to allocate their attention to the parafovea in order to effectively encode letter identity and letter position.

Whilst children with dyslexia showed orthographic preview effects demonstrating that letter position was encoded parafoveally and independently to letter identity, these effects did not occur within single fixation duration or first fixation duration. This is in contrast to the results found for the 10 year old typically developing children matched for chronological age. This difference in parafoveal processing suggests that dyslexic readers gain orthographic preview benefits at a delayed time frame compared to their peers. Whilst they do encode orthographic information parafoveally, it takes longer for dyslexic readers to process this information relative to their non-dyslexic peers. Delayed orthographic parafoveal processing may occur due to dyslexic readers requiring greater attentional resources for foveal processing (compared to their peers), perhaps due to difficulties in phonological decoding and thus having less attentional resources for parafoveal processing (Yan et al., 2013). This is consistent with studies demonstrating slower lexical processing for less skilled readers and the proposal of a developmental increase in the rate of lexical processing (Reichle, Liversedge, Drieghe, et al., 2013). Furthermore, such results support the findings of Yan et al. (2013) who suggest that dyslexic readers are "less efficient" in their use of parafoveal information compared to chronological age matched controls.

In contrast to the differences found within dyslexic readers and chronological age matched children, the orthographic preview benefits demonstrated by dyslexic readers and children matched for reading age showed a similar pattern. For both dyslexic children and 8 year old typically developing children matched for reading age, the typical orthographic preview effects (a greater benefit for identical previews compared to transposed previews and for transposed previews compared to substituted letter previews) occurred but only during later measures such as gaze duration, go-past time, and total reading time. In fact, the only difference in preview benefit between readers with dyslexia and children matched for reading age occurred within go-past time where readers with dyslexia showed a marginally larger TL effect.

Whilst it is hard to interpret marginal findings, such results could suggest that dyslexic readers have an increased level of flexibility for orthographic processing of letter position information compared to children matched for reading age. It is important to note, however, that numerically dyslexic readers did not show a benefit of transposed-letter previews compared to identical previews, which suggests that the dyslexic children were not encoding letter position information in go-past time. In which case, it is difficult to conclude that letter position was encoded independently to letter identity, as there is no evidence of initial letter position encoding. In fact, such result suggests that dyslexic readers are only encoding letter identity during go-past time. As discussed in Chapter 2, parafoveal preview benefits are typically measured using first fixation duration, single fixation duration and gaze duration, as parafoveal processing manipulations occur before the reader fixates the word. Consequently, the effects of the parafoveal manipulation typically occur within the initial eye movements made onto that word. Measures of go-past time and total reading time, whilst useful for indicating differences in reading groups, are generally not as useful when exploring the effects of a parafoveal manipulation. Whilst the results from go-past time and total reading time are somewhat tricky to interpret, the results from first fixation duration, single fixation duration, and gaze duration appear to be clearer. Indeed, dyslexic readers show similar orthographic preview effects to those found for reading age matched children for all early measures. As such, it appears that the degree to which children engage in orthographic parafoveal processing is determined by their reading ability. Therefore, the differences in parafoveal processing abilities found between dyslexic children and chronological age matched children (less efficient or delayed parafoveal processing) are likely to be due to dyslexic readers' lower reading skill rather than a specific cognitive deficit for readers with dyslexia.

The current study also provided evidence that foveal eye movement patterns were indicative of reading skill, where chronological age matched children showed shorter, first fixation durations, single fixation durations, total sentence reading times, average fixation duration and less fixations than both the less skilled reading groups (children with dyslexia and reading age matched children). There were, however, also differences between the eye movement patterns of children with dyslexia and reading age matched children; dyslexic readers showed additional linguistic processing difficulties during gaze duration and total reading time and evidence of an increased fixation count on the target. Consequently, as the reading age matched children were specifically selected to have a similar reading age to that of the children with dyslexia, this suggests that the foveal eye movement patterns of dyslexic readers are not solely due to their poor reading ability and phonological skills. In fact, such result suggests that, during foveal processing, there is a specific reading deficit for children with dyslexia compared to children who read at the same level; their eye movement behaviour is not solely explained by their reading ability. It appears that although children with dyslexia make similar length fixation durations to typically developing children with a similar reading age, dyslexic children require additional fixations within a word, which results in increased gaze durations and reading times.

Refixations typically occur due to a requirement for a second visual sampling (Blythe et al., 2011). In particular, they tend to occur when a reader's initial fixation is unable to provide sufficient visual information for lexical identification. This is often the case for longer words, due to limitations in perceptual span (Blythe, 2014; Blythe et al., 2011). However, note that, as discussed in Chapter 1, children as young as 7 years old have been found to demonstrate normal reading patterns during the disappearing text paradigm (Blythe et al., 2009); such a result demonstrates that children are able to encode visual information effectively within the initial 40ms of a fixation (in order to begin normal lexical identification), with continued linguistic processing occurring throughout the remainder of the fixation. For this reason, it is not completely clear as to why readers need to make additional fixations if visual sampling can occur within the initial 40ms of a fixation. Blythe et al. (2011) suggest refixations may occur for a number of reasons, such as: limitations in visual sampling due to a reduced perceptual span, continued linguistic processing in which the currently fixated word is yet to be lexically activated thus another fixation is programmed to that word, or, due to "habit" where children continue to make additional fixations although they are not strictly necessary. Blythe et al. (2011) suggest that it is unlikely for there to be a single reason why children make refixations during reading, and, it is expected that a combination of these factors contribute to the requirement for refixations.

Within the current experiment, dyslexic readers made more fixations compared to typically developing children matched for reading age. As discussed above, one explanation for increased refixations may be due to limitations in visual sampling. In fact, compared to non-dyslexic readers, dyslexic readers have been found to show both a reduced perceptual span (Rayner et al., 1989) and limitations in the VA span (recall the VA span corresponds to the amount of orthographic information that can be simultaneously processed when reading, see Chapter 1 for detailed discussion of the VA span; Bosse et al., 2007; Prado et al., 2007; Valdois et al., 2004). As such, dyslexic readers may not be able to encode enough information within one fixation and therefore need to make additional fixations. Whilst it is possible that difficulties in phonologically processing the fixated word causes increased foveal load and reduces perceptual span, a reduced VA span has been found to occur in dyslexia independent of phonological difficulties (Bosse et al., 2007; Prado, Dubois & Valdois, 2007). Furthermore, both perceptual span and VA span are (at least to some extent) determined by visual attention, therefore, dyslexic readers may make more fixations compared to typically developing children matched for reading ability due to specific deficits in attention allocation in relation to the foveal word or through restrictions in attention due to difficulties in phonological processing associated with the fixated word (i.e. increased foveal load).

Whilst it is possible that dyslexic readers have restricted attention allocation and, therefore, need to make additional fixations, such an explanation appears somewhat contrary to the findings that dyslexic readers can encode orthographic information from the parafoveal word during reading (detailed within both the current chapter and Chapter 3). It may, however, be possible that attention is not allocated efficiently across the foveal and parafoveal words for readers with dyslexia. In line with this reasoning, previous studies have reported increased parafoveal processing in dyslexic readers (Geiger & Lettvin, 1987; Geiger, Lettvin, & Zegarra-Moran, 1992; Lorusso et al., 2004) and also confusability when encoding foveal and parafoveal information during RAN (Jones, Branigan, & Kelly, 2009; Jones et al., 2008; 2013). It is possible, therefore, that dyslexic readers have widely distributed attention, and, instead of prioritising attentional resources to foveal processing, they equally encode all information within their perceptual span.

It is important to note that the current evidence for parafoveal processing in dyslexic reading (demonstrated within the current chapter and Chapter 3) only focuses upon orthographic parafoveal processing. Accordingly, it is possible that while dyslexic readers orthographically encode foveal and parafoveal information, they might have a specific difficulty in the foveal (and parafoveal) processing of phonological information. In fact, within the eye movement and reading literature, it is generally accepted that saccades to the next word are programmed when some level of lexical activation occurs (such as the completion of word identification, Morrison, 1984; or the completion of an early stage of lexical processing called the familiarity check, Pollatsek et al., 2006; Reichle et al., 1998) and this lexical activation requires both orthographic and phonological information. As such, a specific difficulty with foveally encoding phonological information would disrupt lexical activation and thus prevent the next saccade being programmed to word *N*+1. Note that explanations that rely upon deficits in phonological processing do appear somewhat counterintuitive since dyslexic readers showed increased refixations compared to typically developing children matched for reading ability (i.e. phonological skills). It is, however, important to acknowledge that the tests used to determine phonological skills did not take into account the time taken to complete phonological processing. Dyslexic readers may have demonstrated similar phonological capabilities, but it may have taken them longer to activate these phonological representations and articulate their answers. As discussed, dyslexic readers are known to have difficulties with decoding (mapping phonology onto orthography; Liberman, 1973; Snowling, 1995; Snowling, 2000; Snowling & Hulme, 2012; Stanovich, 1988) and this difficulty might be specific to accessing the representations (Boets et al., 2013). Slower lexical activation could also be explained by SAS (sluggish attention shifting, discussed within Chapter 1), where readers with dyslexia struggle to disengage attention when visual or auditory stimuli is presented within a rapid sequence; their attention is 'sluggish' and engaging and disengaging attention takes longer for a dyslexic reader than a typical reader (Hari, & Kiesilä, 1996; Hari & Renvall, 2001; Helenius, et al., 1999; Merzenich et al., 1993).

Finally, another possible explanation for increased refixations relates to landing positions. Whilst there were no significant differences between the landing positions of the three reading groups within the current results, dyslexic children showed a numerical trend for the typical pattern of results in which they made fixations that landed earlier within a word compared to their non-dyslexic peers (De Luca et al., 2002; Hawelka et al., 2010; MacKeben et al., 2004; Pan et al., 2014). Whilst the difference was not statistically significant, the numerical trend suggested that dyslexic readers made fixations earlier within the target word compared to both chronological age matched children and reading age matched children. Although it is hard to draw conclusions based on numerical trends, if readers with dyslexia do in fact have landing positions which occur earlier in a word compared to typically developing children matched for reading age, this would suggest that dyslexic readers have a dyslexic specific deficit (that is not explained solely by their reading age) which impacts their ability to effectively target their saccades to the preferred viewing location. Additionally, it is possible that because dyslexic readers land closer to the beginning of the word (in comparison to non-dyslexic readers who land toward the middle), they are more likely to make extra fixations. In fact, when typically developing children make fixations positioned at the beginning of the word, they are more likely to refixate that word (Joseph et al., 2009; McConkie et al., 1991; Vitu et al., 2001). Thus, it is possible that these early landing positions are in fact a dyslexic specific deficit that then impacts the requirement for additional fixations during reading.

It is, however, less clear as to why dyslexic readers may make these non-optimal landing positions in the first instance. Indeed, parafoveal information is typically used to help guide eye movements (Rayner, 1998; Sereno & Rayner, 2000);

therefore, deficits in parafoveal processing may impact a reader's ability to target their saccades. However, within both the current experiment and Experiment 1 (Chapter 3) of this thesis, dyslexic readers demonstrated evidence of parafoveal processing for the initial letters of the parafoveal word, thus readers with dyslexia do gain some form of parafoveal information. Although the current thesis demonstrates parafoveal processing in readers with dyslexia, Rayner et al. (1989) demonstrated that readers with dyslexia do, in fact, have a reduced perceptual span. It is, therefore, possible that whilst readers with dyslexia are able to gain orthographic parafoveal preview benefits from the initial letters of the parafoveal word, they may not code enough parafoveal information (information such as word length or spaces between words requires parafoveal processing of information beyond the initial letters of a word). In which case, it is possible that although dyslexic readers can encode orthographic information from the initial letters of the parafoveal word, they do not receive enough parafoveal information to correctly target their saccades. It must be noted, however, that early landing positions may also be conducive for serial, sublexical word decoding (MacKeben et al., 2004; Marx et al., 2016; Hawelka et al., 2010), in which case these early landing positions may represent a reliance upon a more effortful reading strategy which may also impact the ability to parafoveally pre-process information, resulting in non-optimal landing positions and a requirement for more refixations.

Altogether, there are a range of explanations as to why dyslexic readers show differences in refixation durations compared to typically developing children matched for reading age. Whilst the current results cannot address these competing explanations, it provides an interesting line of enquiry for further research, including exploring how phonological deficits manifest during foveal and parafoveal processing (Chapter 5 explores phonological parafoveal processing for dyslexic adults).

4.5 Chapter Summary

This chapter explored orthographic parafoveal processing for dyslexic children, typically developing children matched for chronological age and typically developing children matched for reading age. In support of the adult data, dyslexic children demonstrated the ability to allocate their attention to the parafovea and parafoveally process orthographic information. Indeed, they too encoded letter identity information independently to letter position within the parafovea. Whilst dyslexic readers showed a different time course during parafoveal processing compared to chronological age matched children, dyslexic readers parafoveally processed orthographic information similarly to typically developing children matched for reading age. Thus, the current experiment demonstrated that dyslexic parafoveal processing is determined by their reading skill and dyslexic readers do not appear to have a specific deficit relating to attentional allocation during parafoveal processing. However, dyslexic readers exhibited foveal eye movement patterns that differed to both typically developing children matched for chronological age and typically developing children matched for reading age. In fact, dyslexic children made more refixations on the fixated word compared to typically developing children matched for reading age, thus demonstrating that dyslexic readers do show a dyslexic specific deficit that impacts the processing of the fixated word, resulting in a requirement for additional fixations. It is, however, less clear what might cause such deficit. The next chapter extends the current exploration of orthographic parafoveal processing to determine whether dyslexic readers can parafoveally encode phonological information.

Chapter Five: Experiment 3

5.0 Chapter overview

Chapters 3 and 4 of this thesis established that both dyslexic adults and dyslexic children do gain parafoveal preview benefits during reading. The results showed that dyslexic readers gained preview benefits from orthographic information presented parafoveally; both children and adults with dyslexia encoded letter identity and letter position information from the parafovea. Whilst these results provide useful findings in relation to dyslexia, these previous chapters did not provide examination of phonological parafoveal processing. It is, therefore, still unclear whether readers with dyslexia are able to encode phonological information from the parafovea during reading. As discussed in earlier chapters, dyslexic readers have specific difficulties with mapping phonology to orthography (Liberman, 1973; Snowling, 1995; Snowling, 2000; Snowling & Hulme, 2012; Stanovich, 1988); therefore, whilst dyslexic readers were able to encode orthographic information parafoveally, there may be deficits in dyslexic phonological parafoveal processing. The following chapter details the final experiment within this thesis and explores phonological parafoveal processing in adults with dyslexia.

Phonological parafoveal processing in adults with dyslexia

5.1 Introduction

There is a body of research demonstrating that skilled readers encode phonological information during parafoveal processing (Ashby & Rayner, 2004; Ashby et al., 2006; Blythe et al., 2018; Chace et al., 2005; Choi & Gordon, 2014; Dare & Shillcock, 2013; Liu, Inhoff, Ye, & Wu, 2002; Miellet & Sparrow, 2004; Pollatsek et al., 1992; Rayner, Sereno, Lesch, & Pollatsek, 1995; Sparrow & Miellet, 2002; Tiffin-Richards & Schroeder, 2015; Tsai, Lee, Tzeng, Hung, & Yen, 2004). In fact, one of the earliest studies to explore phonological preview benefits during parafoveal processing was that of Pollatsek et al. (1992) who used the boundary paradigm to demonstrate phonological preview benefits for homophone previews compared to orthographically similar previews in measures of single word naming latency.

Homophones are words that are orthographically and semantically dissimilar but phonologically identical (e.g., *genes*, *jeans*) and allow for an examination of whether phonological information is encoded from the parafoveal word and, therefore, used to facilitate the processing of the target word (which shares phonological form) once fixated. Within the first of two experiments detailed in Pollatsek et al. (1992), participants were required to fixate upon a fixation cross that was presented at the center of a screen. Once their fixation was stable, the experimenter triggered a word to appear within the parafovea, participants then made a saccade to that word (triggering the boundary paradigm and the word to change), read and named the word. The parafoveal word manipulations were: 1) an identical preview (e.g. *brake*, or, *plate*), 2) a visually similar preview which was either a homophone (e.g. *break*) or orthographically similar preview (e.g. *pleat*), or 3) a different preview which was a word of equal length and similar word shape but differed in all letter positions (e.g. *doubt*, or, *grill*). Therefore, each set of preview word stimuli (e.g. *break*, *brake*, *doubt,* or*, plate, pleat, grill*) only had one visually similar preview that was either a homophone or an orthographically similar word. As mentioned, homophone previews were included to explore phonological preview benefits as the words share their phonological form. In addition to homophones, orthographic control previews were used in attempt to determine whether phonological information was encoded and used to facilitate preview benefit independently to the preview benefits found for orthographic information. Many homophone previews are orthographically similar to the target word (e.g. *break*, and, *brake*), as such orthographic control previews were required to control for letter similarity within the preview conditions. However, due to the experimental design, there was not a direct comparison between homophone previews and orthographically similar previews for each of the sets of preview word stimuli (e.g. *break*, *brake*, *doubt*), as only one of these preview manipulations occurred within a set of preview stimuli. This occurred due to "the constraints of English" (Pollatsek et al., 1992, p. 152), which made it difficult to exert the level of control required to include all manipulations for all sets of stimuli. Nevertheless, in this initial experiment, Pollatsek et al. (1992) demonstrated that homophone previews were named quicker than the orthographically similar controls, thus demonstrating phonological information was encoded parafoveally and helped facilitate the naming on the word once fixated. Whilst this experiment provided initial evidence for phonological preview benefits, this was demonstrated during single word naming and is not necessarily generalisable to natural sentence reading.

In their second experiment, Pollatsek et al. (1992) used the boundary paradigm to explore homophone previews during silent sentence reading. In this experiment, the following parafoveal preview manipulations were used to examine phonological parafoveal processing: 1) an identical preview (e.g. *beach*), 2) a homophone preview (e.g. *beech*), 3) an orthographic control preview (e.g. *bench*) and finally 4) an orthographically and phonologically dissimilar preview (e.g. *house*). Thus, within their second experiment, Pollatsek et al. (1992) included a direct comparison for homophone and orthographic control previews. Pollatsek et al. (1992) found that, during first fixation durations, homophone previews resulted in a greater preview benefit than the orthographic control previews. Furthermore, whilst the effect was not significant during gaze duration, there was a trend in the mean values that suggested greater preview benefit for homophone previews compared to orthographically similar previews. This indicates that, as well as encoding orthographic information parafoveally, skilled readers get additional preview benefit from encoding phonological information in the parafovea during sentence reading. Analysis was also conducted to compare the homophone preview benefit to the dissimilar condition; homophone previews provided greater preview benefit compared to dissimilar previews in both first fixation duration and gaze duration. There was also a trend in the means, to suggest orthographic control previews resulted in greater preview benefit compared to dissimilar previews, however, this effect was not statistically significant. Finally, the advantage for identical previews compared to homophone previews was not significant for either first fixation duration or gaze duration. Thus suggesting, in this instance, homophone previews activated the base word as effectively as the correct parafoveal preview.

Whilst Pollatsek et al. (1992) provided evidence for phonological parafoveal preview benefits that occur in addition to benefits from orthographic parafoveal processing, the authors noted that, as predicted, the effects were not “huge”. The high correlation between orthographic control previews and phonology-based previews (such as homophones) makes it particularly difficult to establish large differences between the preview benefits for these two conditions. It is, therefore, typically difficult to determine whether there are distinct orthographic and phonological components of parafoveal preview. Furthermore, research has demonstrated that for occasions when the first two letters of the previews overlap (even when they are not homophones), preview benefits are close to those obtained when the previews were identical (Balota et al., 1985; Rayner et al., 1980), thus limiting the possibility for large increases in preview benefits for homophone and orthographical control previews when the manipulation occurs across 2 or more letters. In fact in their study, Pollatsek et al. (1992) demonstrated that phonological preview benefits were particularly hard to identify when there was greater visual overlap between the preview conditions. It is, however, important to note that Pollatsek et al. (1992) particularly decided to use homophones to explore phonological parafoveal preview benefits as earlier work by Rayner et al. (1980) was unable to establish phonological preview benefits using a manipulation of single phonemes.

In their study, Rayner et al. (1980) used the boundary paradigm to examine preview benefits upon the target word (e.g., *plane*) when the parafoveal preview was manipulated for either an identical initial phoneme (e.g., *prune*) or a dissimilar initial phoneme (e.g., *phone*). Rayner et al. (1980) found no evidence of phonological preview benefits during this initial study, where the manipulation was limited to the initial phoneme. As the manipulation of phonology was limited only to the initial phoneme, the phonological overlap between the target word and the phonologically manipulated preview was very small and this reduced likelihood for Rayner et al. (1980) to find phonological preview benefits. Therefore, within their later study Pollatsek et al. (1992), specifically selected homophones to examine phonological preview benefits as they provide greater phonological overlap (i.e. across the whole word) compared to manipulating just one phoneme. In fact, these studies demonstrate the difficulties in finding phonological preview benefits as both too much and too little phonological overlap can hinder the ability to find such effects. However whilst it can be challenging to establish these effects, there are a number of studies demonstrating phonological parafoveal preview benefits in a range of languages, for example English (Ashby et al., 2006; Chace et al., 2005; Choi & Gordon, 2014; Tiffin-Richards & Schroeder, 2015), French (Miellet & Sparrow, 2004), and Chinese (Liu et al., 2002; Pollatsek et al., 2000; Tsai et al., 2004).

In further exploration of phonological parafoveal processing for English adult readers, Ashby et al. (2006) manipulated internal vowel phonemes (e.g. *chirp* compared to *cherg* and *chorg*). They compared phonologically similar internal vowel phonemes and phonologically dissimilar internal vowel phonemes, and found that non-words that share phonologically similar internal vowel phonemes to the target word resulted in greater preview benefits than non-words with dissimilar internal vowel phonemes. Therefore, Ashby et al. (2006) provide additional evidence for phonological parafoveal processing, but through the manipulation of vowels rather than full homophones. In addition, Miellet and Sparrow (2004) provided evidence for phonological preview benefits in their sample of French adult readers.

Within their study Miellet and Sparrow (2004) used the boundary paradigm during silent sentence reading to compare the parafoveal previews benefits of the following preview conditions: 1) an identical preview (e.g. *chaise*), 2) a spelling control pseudoword preview (e.g. *choise*), and 3) a homophone pseudoword preview (pseudohomophones; e.g. *cheise*). Spelling control pseudoword previews were non-words that were orthographically similar to the identical preview. Pseudohomophone previews were non-words that shared the same phonology but differed in orthography. Miellet and Sparrow (2004) found that pseudohomophone previews resulted in greater preview benefit compared to previews that were non-word non-homophones. They used pseudoword stimuli rather than real word stimuli to determine how phonological parafoveal information is extracted from the parafoveal word. In fact, the findings that readers did gain phonological preview benefits during parafoveal processing of pseudowords suggests that parafoveal information is encoded through assembling sub-lexical information from grapheme-phoneme correspondences rather than through a complete orthographic representation of the word. Thus, Miellet and Sparrow (2004) provide evidence for phonological parafoveal preview benefits, but also findings to suggest that readers do not need a full orthographic representation of the parafoveal word before phonological preprocessing occurs. This is particularly interesting when considering dyslexic parafoveal processing as dyslexic readers have been found to have a reduced perceptual span (Rayner et al., 1989). Although Chapters 3 and 4 provide evidence of dyslexic parafoveal processing for the initial letters of the parafoveal word, dyslexic readers may have limitations in attention allocation that prevent the orthographic preprocessing of the entire parafoveal word. It is, therefore, important to establish that phonological parafoveal previews benefits do not rely upon a full orthographic representation, and, as such the "amount" of information extracted from the parafovea (i.e. from how far into the parafovea readers can extract information) might not necessarily impact the type of information extracted (i.e. orthographic or phonological).

In a further study of phonological parafoveal processing in skilled adult readers, Choi and Gordon (2014) also examined phonological preview benefits using pseudohomophones. They used two different methods to examine phonological parafoveal processing. In Experiment 1 Choi and Gordon (2014) used the boundary paradigm to examine preview benefits for the following preview manipulations: 1) an identical preview (e.g., *brain*), 2) a pseudohomophone preview (e.g., *brane*), and 3) an orthographic control preview (e.g., *brant*). During single fixation duration, first fixation duration and gaze duration, they found that identical previews resulted in greater preview benefit compared to both pseudohomophone and orthographic control previews, with no difference between the pseudohomophone and orthographic control previews. Thus, in this experiment, Choi and Gordon were unable to find evidence in support of additional parafoveal processing benefit for phonological information compared to the equivalent orthographic match. Such results are contrary to Miellet and Sparrow (2004) but are supported by studies that have demonstrated difficulty in finding phonological benefits specifically for pseudohomophones (Lee, Kambe, Pollatsek, & Rayner, 2005; Lee et al., 1999).

In their second Experiment, Choi and Gordon (2014) used the boundary paradigm to examine preview benefits for the following preview manipulations: 1) an identical preview (e.g. *plain*), 2) a homophone preview (e.g. *plane*), and 3) an orthographic control preview (e.g. *plate*). Thus, in this experiment, they used homophone previews to examine phonological preview effects rather than pseudohomophone previews. In support of Experiment 1, they found that identical previews resulted in greater preview benefit compared to both homophone and orthographic control previews, particularly for occasions in which the previous launch site was five or fewer characters from the left of the beginning of the target word. This demonstrates the importance of nearby launch sites for parafoveal preview benefits during reading. In fact, such a finding is interesting in relation to dyslexic readers as they often show earlier landing positions within a word compared to non-dyslexic readers (De Luca et al., 2002; Hawelka et al., 2010; MacKeben et al., 2004; Pan et al., 2014), and, may therefore have greater restrictions in parafoveal processing.

In contrast to Pollatsek et al. (1992), Choi and Gordon (2014) were unable to establish a significant difference between the homophone and orthographic control previews. There were, however, numerical trends in the data to indicate an additional benefit of homophone previews compared to orthographic control previews. In fact, similarly to Pollatsek et al. (1992), Choi and Gordon (2014) suggested that a lack of a significant effect might be due to the high degree of orthographic overlap between the homophone previews and orthographic control previews compared with the target word.

Whilst there is increasing evidence of phonological parafoveal processing during reading for skilled adult readers (Ashby & Rayner, 2004; Ashby et al., 2006; Blythe et al., 2018; Chace et al., 2005; Choi & Gordon, 2014; Dare & Shillcock, 2013; Liu et al., 2002; Miellet & Sparrow, 2004; Pollatsek et al., 1992; Rayner et al., 1995; Sparrow & Miellet, 2002; Tiffin-Richards & Schroeder, 2015; Tsai et al., 2004), there is very little known about the development of phonological parafoveal processing and how reading ability impacts phonological parafoveal processing. As discussed within earlier chapters of this thesis, Tiffin-Richards and Schroeder (2015) explored both orthographic and phonological parafoveal processing for both children and adult German readers. Specifically, they used an identical preview, a pseudohomophone preview, and an orthographic control preview (examples are provided in German; e.g. *Reis*, *Rais*, *Ruis*, respectively) during a boundary paradigm study of silent sentence reading.

For adult readers Tiffin-Richards and Schroeder (2015) found no evidence of increased preview benefit for pseudohomophones compared to the orthographic control previews, however, they did find evidence to support that identical previews provide significantly greater preview benefits compared to pseudohomophone previews. For children, there was a different pattern of results; children demonstrated a significant preview benefit for pseudohomophones compared to orthographic control previews which occurred significantly within single fixation duration and gaze duration and, numerically, in first fixation duration (the effect was not statistically significant for first fixation duration). Interestingly, for children, pseudohomophones provided preview benefits that were similar to those for identical previews. Thus, for children, pseudohomophones equally activated the lexical representation of the target word compared to the identical preview, indicating that phonological information may play an important role in parafoveal processing for beginning readers.

For adults, however, phonological information appeared less important for parafoveal processing compared to orthographic information (at least for the German speaking adults tested by Tiffin-Richards and Schroeder, 2015). In their study, Tiffin-Richards and Schroeder (2015) demonstrated that adult readers relied more on orthographic information to provide parafoveal preview benefit during reading. Recall, however, there is a body of work demonstrating skilled adult readers do gain parafoveal preview benefit from phonological information during reading across a range of languages.

Whilst the findings from Tiffin-Richards and Schroeder (2015) are useful in developing our understanding of phonological parafoveal processing in German children, the results found for skilled adult readers contradict studies of phonological parafoveal processing for skilled English readers (Ashby et al., 2006; Blythe et al., 2018; Pollatsek et al., 1992). As noted above, however, it is particularly hard to establish phonological preview benefits, especially when using pseudohomophones (Lee et al., 2005; Lee et al., 1999). Another point to consider, when comparing the work of Tiffin-Richards and Schroeder (2015) to studies of English phonological preview benefits, is that of orthographic density. Indeed, within the results reported in this thesis thus far, there have been findings that are contrary to those found by Tiffin-Richards and Schroeder (2015) in their study of German readers. Specifically, findings from Chapter 3 and Chapter 4 demonstrated that both English adults and children showed orthographic preview benefits, whereas for German readers, Tiffin-Richards and Schroeder (2015) found that adults showed orthographic preview benefits, but children showed little evidence of such effects. Thus, it is possible that for English readers, parafoveal processing develops differently compared to German readers. This may be due to English being a less transparent language than German as this may impact the development of orthographic processing (McDougall et al., 2010). Furthermore, research has also demonstrated a strong impact of phonological information during English reading (Rastle & Brysbaert, 2006). It is, therefore, possible that English readers, particularly during development, show differences in both orthographic and phonological parafoveal processing of information during reading compared to German readers.

Further to the results from Tiffin Richards, one study by Chace et al. (2005; also discussed within Chapter 3) explored phonological preview benefits during reading for a sample of university readers who were divided into groups of less skilled and skilled reading adults. Chace et al. (2005) aimed to extend the findings of Pollatsek et al. (1992) by exploring the impact of reading skill upon phonological parafoveal processing. They predicted that less-skilled readers would gain less preview benefit from phonological parafoveal information compared to more skilled readers. This was predicted on the basis that less skilled readers might allocate more of their resources to processing the currently fixated (foveal) word, thus leaving less capacity available to effectively encode the parafoveal word. Similarly to Pollatsek et al. (1992), Chace et al. (2005) used the boundary paradigm with the following preview conditions: identical to preview (words that were identical to the target word, e.g. *beach*), a homophone of the target word (e.g. *beech*), an orthographic control preview (e.g. *bench*), or a random letter string (e.g. *jfzrp*).

Using a sample of 23 adult readers (the poor readers were excluded for purposes of replication), Chace et al. (2005) were able to demonstrate phonological parafoveal processing similar to that of Pollatsek et al. (1992). In fact, Chace et al. (2005) found a significant preview benefit for homophones compared to the orthographic control previews in gaze duration, and this was further supported by a numerical trend in first fixation duration (which did not reach significance). Such results further indicate that using homophones to manipulate phonological preview can provide evidence of phonological preview benefits in skilled readers. Chace et al. (2005) demonstrated that skilled readers were able to encode phonological information during parafoveal processing, and that phonological information provided a preview benefit greater than that of orthographic information. In addition to replicating the results of Pollatsek et al. (1992), a second set of analyses was conducted to explore the effects of reading skill on phonological parafoveal processing. In order to explore this, Chace et al. (2005) divided their sample into two reading groups, “more skilled” (N=13) and “less skilled” readers (N=13), and this group distinction was based on the participants’ scores on the vocabulary and reading comprehension subtests of the Nelson-Denny Reading Test (Brown et al., 1981).

Chace et al. (2005) found that for first fixation duration, there was a main effect of reading skill with more skilled readers having shorter first fixation durations compared to less skilled readers. In addition, there was an interaction in which there was no significant increase in preview benefit for homophone previews compared to orthographic control previews for skilled adult readers; thus, although there was a numerical trend to support phonological parafoveal processing in more skilled readers, this effect was not significant during first fixation duration. For less skilled readers, however, there was a significant effect but this occurred in the opposite direction to more skilled readers; less skilled readers showed greater preview benefit from orthographic control previews compared to homophone previews. However, Chace et al. (2005) note that, whilst this is a significant finding, it relied upon two of the less skilled readers and, consequently, the effect was no longer significant when these individuals were removed from the analysis. Thus, for first fixation duration, neither reading group showed a significant benefit of homophone previews compared to orthographic control previews.

For gaze duration, the pattern of results was as Chace et al. (2005) had predicted. Although there was no main effect of reading skill, there was an interaction demonstrating that more skilled readers showed increased preview benefit for homophone previews compared to orthographic control previews. Less skilled readers, however, showed no significant difference between these two preview conditions. Therefore, indicating that the less skilled readers did not encode phonological information from the parafovea whereas skilled readers did. It is, however, important to note that, in contrast to the more skilled readers, the less skilled readers did not demonstrate preview benefit for identical previews compared to random previews. Chace et al. (2005) consequently concluded that less skilled readers showed no evidence of any type of preview benefit, and that they were likely to be devoting more attention to encoding the fixated word, leaving limited attentional resources left for parafoveal processing. Such finding is contrary to the results detailed in earlier chapters of this thesis (Chapter 3 and 4), where dyslexic adults and children showed orthographic parafoveal processing benefits during reading. There are, however, a number of differences between these studies that may explain the differences in results.

One difference between the experiments detailed in Chapters 3 and 4 and the study by Chace et al. (2005), is the frequency scores of the pre-target words. Within the studies detailed in this thesis (in Chapter 3 and 4), the pre-target words were specifically selected to be high frequency words, in order to increase the likelihood of attentional resources being available for parafoveal processing. In contrast, Chace et al. (2005) used low frequency pre-target words, which may have required increased foveal attention in order to encode the fixated word, compared to attention required for high frequency pre-target words. It is, therefore, possible that the stimuli used by Chace et al. (2005) consequently restricted the attentional resources for their sample of less skilled readers, which meant they were unable to gain any benefit from parafoveal information during reading. There is, however, an alternative explanation for the differences in preview benefit found within Chapter 3 and 4 of this thesis and that found by Chace et al. (2005). It is possible, that the samples used within these studies represent separate groups of readers with different types of reading difficulties.

Whilst the findings from Chace et al. (2005) help to develop our understanding of how reading difficulties may impact parafoveal processing, it is unclear to what extent their results generalise to dyslexic readers. To clarify, Chace et al. (2005) used measures of vocabulary and reading comprehension to determine the less skilled reading group within their sample. Dyslexia, however, is defined by difficulties with decoding (Liberman, 1973; Snowling, 1995; Snowling, 2000; Snowling & Hulme, 2012; Stanovich, 1988) and studies that explore dyslexia typically use measures of decoding to identify their sample (e.g. Hawelka et al., 2010; Kirkby et al., 2011; Silva et al., 2015; Snowling & Hulme, 2012). In fact, dyslexia and difficulties in reading comprehension (a group known as poor comprehenders) are often considered separate reading disorders with different causes and different treatments (Cain et al., 2000; Cain, 2010; Hulme & Snowling, 2009; Nation et al., 1999; Nation & Snowling, 1998; Snowling & Hulme, 2012; Stothard & Hulme, 1995). Thus, the sample used by Chace et al. (2005) may not reflect dyslexic deficits and the conclusions may not extend to readers with dyslexia. Such suggestion is supported by the fact that the less skilled readers in Chace et al. (2005) showed increased first fixation durations compared to the more skilled reading group, but no differences in gaze durations. Indeed, during reading, it is unusual for dyslexic readers to have similar gaze durations to skilled adult readers; dyslexic readers typically show increased gaze durations compared to skilled readers (Hawelka et al., 2010; Hutzler & Wimmer, 2004; Yan et al., 2013) and this is supported in both Chapter 3 and Chapter 4 of this thesis. Therefore, as the sample of readers used within Chace et al. (2005) show differences in both foveal and parafoveal processing compared to samples of dyslexic readers, it is possible that they are in fact different types of poor readers, and that the underlying deficits that are causing their reading difficulties impact parafoveal processing in different ways. Consequently, further work is required to understand phonological parafoveal processing for readers with dyslexia.

In addition to the analysis for the two reading groups, Chace et al. (2005) also conducted analyses with reading skill as a continuous variable in regression analyses using their full sample of 32 participants (both more and less skilled readers). The Nelson-Denny (Brown et al., 1981) percentile rank scores were regressed on the differences between the homophone preview and the orthographic control previews. For both first fixation duration and gaze duration, they found a significant effect, indicating that the increased preview benefit for the homophone preview, compared to orthographic control previews, was greater for more skilled readers compared to less skilled readers, thus, indicating that reading skill (as measured by the Nelson Denny tests of vocabulary and reading comprehension; Brown et al., 1981) impacts upon a reader's ability to encode phonological information during parafoveal processing. It is, however, still unclear as to whether difficulties in decoding may impact a reader's ability to parafoveally process phonological information.

In addition to Chace et al. (2005), Bélanger et al. (2013) explored phonological parafoveal processing for skilled adult readers and groups of deaf readers. It has been suggested that deaf readers may only develop partial or underspecified phonological representations (Kelly & Barac-Cikoja, 2007), perhaps similar to dyslexic readers; however, as discussed by Bélanger et al. (2013), the role of phonological processing in deaf readers is still under debate. Similarly to previous studies with skilled adult readers, Bélanger et al. (2013) demonstrated phonological preview benefits for skilled readers. However, whilst deaf readers demonstrated parafoveal processing abilities during reading, they showed no benefit of phonological parafoveal processing. In contrast to Bélanger et al. (2013), Blythe et al. (2018) demonstrated that their sample of teenagers with permanent childhood hearing loss did exhibit phonological parafoveal processing during silent sentence reading. Blythe et al. (2018) suggest these discrepancies may occur to differences in the way in which the participants process phonological information. Indeed, the sample criteria for participants was different across the two studies. The participants in the Blythe et al. (2018) study had a greater range of level of hearing loss (30–126 dB SPL), and all used oral language as their primary means of communication.

Whereas, those in the Bélanger et al. (2013) study, were severely to profoundly deaf (hearing loss > 71 dB SPL) and used sign language (ASL) as their primary means of communication. Whilst Blythe et al. (2018) found that deaf readers' level of hearing loss had no impact on phonological processing during reading, the two groups also differed in their method of communication which would impact their phonological processing. Thus although it is unclear exactly how phonological processing occurs for deaf readers, their phonological processing appears to impact their ability to gain phonological preview benefits. Accordingly, if deaf readers do have partial or underspecified phonological representations, then dyslexic readers may show a similar pattern of results during phonological parafoveal processing. There are, however, no studies explicitly looking at phonological parafoveal processing for dyslexic readers during sentence reading.

One study of particular interest to the current line of enquiry is that of Jones et al. (2013). Within their two experiments, Jones et al. (2013) explored both orthographic and phonological foveal and parafoveal processing of information during RAN for groups of skilled and dyslexic adult readers. Jones et al. (2013) used the boundary paradigm to independently manipulate foveal (Experiment 1b) and parafoveal (Experiment 1a) information processing, in order to examine the impact of confusable information. To this end, letter arrays contained target item pairs where the second letter of the pair was orthographically or phonologically similar (and therefore confusable) to the first letter when viewed either foveally or parafoveally.

In Experiment 1a, orthographically confusable (e.g. *b* and *d*) or phonologically confusable (e.g. *g* and *j*) letters were presented parafoveally. Therefore, when the participant fixated upon letter N (e.g. *b*), letter *N*+1 (presented in the parafovea) was confusable to the fixated letter (e.g. *d*). Once the reader made a saccade across the invisible boundary placed between the letter pairs, letter *N*+1 was replaced with a non-confusable letter (e.g. *m*). Thus, the parafoveal letter was no longer confusable once the reader fixated upon it, allowing for the exploration of orthographic or phonological confusability only during parafoveal processing. For skilled adult readers, there was no disruption to gaze duration and naming latency for either orthographic or phonologically confusable information presented parafoveally. Skilled readers were able to minimise any detrimental impact of parafoveal information when the parafoveal information was incorrect. Therefore, whilst skilled readers may have encoded the incorrect information parafoveally, they were more easily able to reject the incorrect letter information and activate the correct information once it was fixated. Indeed, for skilled adult readers, the incorrect letter information did not disrupt the activation of the foveal letter or the parafoveal letter once it was fixated. Dyslexic readers, however, showed a different pattern of results.

For Experiment 1a, dyslexic readers showed disruption when the available parafoveal information was orthographically similar to the foveal information. Specifically, dyslexic readers showed confusability effects in which gaze durations on letter *N*+1 were longer if the parafoveal preview of that letter was orthographically similar to the previously fixated letter (e.g. fixating letter *d* with a parafoveal preview of *b*). This effect occurred even though *N*+1 was not orthographically similar to N when it was fixated. Whilst gaze durations were disrupted for letter *N*+1, there was no disruption to the processing of letter *N* even though the confusable information was available parafoveally. Such results indicate that dyslexic readers had difficulty inhibiting the parafoveally orthographic confusable letter information that was activated during fixation on letter *N*, when they were then fixating upon and encoding the orthographic information from *N*+1. The previously activated orthographic information (e.g. *b*) interferes with the activation of the newly presented foveal letter (e.g. *m*). As such, it is possible that dyslexic readers are less effective at precise letter activation based on orthographic form; orthographically confusable letters may receive similar activation levels and this may impact their ability to efficiently process orthographically similar letters presented consecutively. Furthermore, as the effects only occurred once the dyslexic readers fixated the letter *N* +1, there appears to be a lag in the interference of parafoveal information, which might suggest that dyslexic readers have slower parafoveal processing. Such suggestion is consistent with Yan et al. (2013) who propose dyslexic readers have less efficient parafoveal processing and could be explained by sluggish attention during parafoveal processing. In fact, the *Sluggish Attentional Shifting* (SAS) Hypothesis (Hari & Renvall, 2001; Lallier et al., 2010) suggests that dyslexic readers struggle to engage and disengage with stimuli presented in a rapid sequence and this makes dyslexic readers slower to process information.

In addition to the above, the finding that dyslexic readers show difficulties in processing consecutive letters that are parafoveally orthographically confusable is in line with research that demonstrates dyslexic readers show parafoveal processing difficulties during studies of lateral masking (Pernet et al., 2006). Although parafoveal orthographic confusability impacted reading for dyslexic readers, there was no impact of phonologically confusable parafoveal information. Such result might suggest that phonologically confusable parafoveal information does not cause disruption for dyslexic readers, as they can effectively inhibit the competing phonological representations and activate the correct representations, or that phonological parafoveal information is not actually parafoveally encoded by dyslexic readers and therefore not a source of confusability.

Further to Experiment 1a, during Experiment 1b Jones et al. (2013) examined the impact of orthographically confusable or phonologically confusable items presented within the fovea (the information was not confusable in parafoveal preview and only became confusable once fixated). In this experiment, skilled readers showed effects of orthographic confusability in foveal processing. Notably, they were slower to process $N + 1$ when it was orthographically similar to N compared to when it was dissimilar. This suggests that for skilled readers, foveal processing can be influenced by the orthographic features of the previous item, and the activation of the previous letter impacts activation of the currently fixated letter. For dyslexic readers, naming latency was longer when foveal information was phonologically similar to the previous letter. The impact of phonological similarity for dyslexic readers occurred in two different ways: naming latency was longer for letter N, therefore suggesting that the new foveal information impacted the phonological assembly and articulation of the previously fixated letter. In addition, the naming of N+1 was impacted; suggesting that dyslexic readers have difficulty disengaging from already articulated phonological codes. There were, however, no effects of orthographic similarity for foveal confusability for dyslexic readers.

Taken together, the results from the two experiments conducted by Jones et al. (2013) demonstrate that, compared to skilled adult readers, dyslexic readers show differences in both foveal and parafoveal processing and this may impact their ability to read fluently. Specifically, dyslexic readers appear to show both independent orthographic and phonological difficulties and these manifest in different ways during foveal and parafoveal processing. Thus, whilst dyslexic readers can encode orthographic parafoveal information (see Chapter 3 and 4), it is still possible that they may have an additional specific deficit that impacts phonological parafoveal processing during reading.

Whilst the conclusions drawn from Jones et al. (2013) during studies of RAN are insightful into foveal and parafoveal processing for readers with dyslexia, it is still unclear whether dyslexic readers show phonological parafoveal processing benefits during reading. As discussed in Chapter 2, RAN and reading differ on a number of levels and, whilst Chapter 3 and Chapter 4 of this thesis provide evidence of orthographic parafoveal processing in dyslexic readers, phonological parafoveal processing may be impacted for dyslexic readers. Indeed, dyslexic readers have difficulty in extracting phonological information from orthographic form (Liberman, 1973; Snowling, 1995; Snowling, 2000; Snowling & Hulme, 2012; Stanovich, 1988); therefore, whilst they may access orthographic information parafoveally, they may not gain any benefit for parafoveal phonological information. Furthermore, as demonstrated by Jones et al. (2013) and Yan et al. (2013), dyslexic readers have slower, less efficient processing of parafoveal information. This is important because, the onset of phonological encoding occurs later in time compared to the onset of orthographic encoding, as orthographic codes are activated prior to phonological codes (Lee et al., 1999; Lee et al., 1999). Therefore, dyslexic readers may extract orthographic information from the parafovea, but may struggle to encode phonological parafoveal information before the next saccade is executed.

The current study aimed to explore phonological parafoveal processing for readers with dyslexia. In order to find phonological parafoveal preview benefits, the current study used the stimuli from Chace et al. (2005). For that reason, the following preview manipulations were used: 1) previews that were identical to the target word (IP; e.g. *beach*), 2) a homophone of the target word (HP; e.g. *beech*), 3) an orthographic control word which was matched to the homophone condition in the amount of orthographic overlap shared with the identical preview (OP; e.g. *bench*), or, 4) a random string of consonants (RP; e.g. *jfzrp*). This design was selected as phonological preview effects can often be difficult to observe, and Chace et al. (2005) already established phonological preview benefits for skilled readers. For skilled adult readers, the usual pattern of preview effects were predicted; identical previews should provide the greatest preview benefit, followed by homophone previews, then orthographic control previews and finally, random previews provide least preview benefit. Specifically, it was predicted that there would be a benefit of homophone previews compared to orthographic control previews for skilled adult readers. For dyslexic readers, it was predicted that there would be a different pattern of results to that of the less skilled readers in Chace et al. (2005). In fact, it was predicted that dyslexic readers would gain preview benefits during reading. As demonstrated in Chapter 3 and Chapter 4, dyslexic readers gained preview benefits from identical previews and orthographic previews. It was, therefore, predicted that dyslexic readers would show benefit of identical and orthographic control previews compared to random previews. However, due the their deficits with phonological processing (Liberman, 1973; Snowling, 1995; Snowling, 2000; Snowling & Hulme, 2012; Stanovich, 1988), dyslexic readers were predicted to have difficulty in encoding phonological information from the parafovea. It was further predicted that there would be an interaction between preview condition and reading group in which dyslexic readers would show no difference between the homophone previews and the orthographic control previews.

5.2 Method

5.2.1 Participants

Participants were 23 university students with developmental dyslexia (mean age of 25 years and 8 months, SD: 7 years and 8 months) and 23 university students without dyslexia (mean age 22 years 8 months, SD: 4 years and 0 months). Students with dyslexia had a prior independent diagnosis of dyslexia and their diagnosis was further supported by deficits in standardised tests of reading ability. All participants were native English speakers with normal or corrected to normal vision and were recruited from Bournemouth University. All participants performed within the normal range on a standardised intelligence test (IQ≥90).

5.2.2 Apparatus

Eye movements were recorded from the right eye using an SR Research Eyelink 1000 eye-tracker. All sentences were presented at a viewing distance of 660 mm on a 22-inch Lacie Electron 22 Blue IV monitor with a screen resolution of 1024 x 768 pixels and a refresh rate of 150 Hz. Sentences were presented in black 14pt Courier New font on a white background.

5.2.3 Design and stimuli

The stimuli used within the current study were taken from Chace et al. (2005), with the exception of some small changes detailed later in this section. As in Chace et al. (2005), four parafoveal preview conditions were presented using the boundary paradigm (Rayner, 1975). Parafoveal previews of the target words were either 1) identical to the target word (IP), 2) a homophone of the target word (HP), 3) an orthographic control word (OP), or 4) a random string of consonants (RP). Sentences were presented on a single line and consisted of up to 80 characters. Target words were 4-6 letter words (mean: 4.51, SD: 0.76) and were preceded by a 4-8 letter pre-target word (mean: 6.02, SD: 1.08). Pre-target and target words were presented towards the middle of the sentence. Pre-target words were chosen to be low frequency words (mean: 22 counts per million, SD: 17, as reported by Chace et al. using word frequency scores from Francis and Kučera, 1982) of medium to long word length in order to increase the likelihood of the participant fixating the word. Target words varied in length and frequency but were matched on both across all conditions; frequency was matched for both identical (mean: 41, SD: 72), homophone (mean: 45, SD: 90) and orthographic control previews (mean: 45, SD: 76), random previews were non-words and do not have frequency values. Identical, orthographic and homophone previews were matched for orthographic overlap; when the homophone condition shared the first two letters of the identical preview, the orthographic control did also. All the target words were normed for predictability and all target words were predicted less than 25% of the time. Target words were also normed for understandability, using a scale of 1-7, the mean rating for all the sentences was 5 or greater, suggesting they were understandable.

In addition, as the experimental stimuli from Chace et al. (2005) were developed for readers of American English, the sentences were piloted with thirteen native British English speakers to make sure they were understandable and coherent. Participants were required to determine whether each sentence “made sense” with a “yes” or “no” response. On occasions where 6 or more of the participants responded to indicate that the sentence did not make sense, these sentences were altered to ensure they were understandable and coherent. Overall, one pre-target word was altered (from *senior* to *graduate*), and one sentence frame was changed to increase understandability for British English readers (note that for this particular sentence, the target word and manipulations remained the same as that within Chace et al., 2005).

The stimuli consisted of 64 sentence frames and for each sentence frame there were 4 versions corresponding to the four parafoveal preview conditions (See Table 5.1 for an example). Three experimental lists were constructed whereby each list contained a different version of each sentence frame and the parafoveal preview manipulations were randomised across the 4 experimental lists so each participant saw sentences from each of the four preview conditions.

The eye movement contingent change boundary was located at the end of the pre-target word and to the left of the space preceding the target word. When the eyes moved past the invisible boundary, the target word changed from the parafoveal preview to the target word. The correct target word then remained in the sentence throughout the remaining duration of the trial. Display changes were typically undetected by the readers as they occurred during a saccade (when visual information is suppressed). Indeed when participants were questioned as to whether they noticed anything unusual during the experiment, very few reported noticing anything and those who did notice something suggested it occurred in a very small number of trials (less than 4 trials) and were unable to explain what had happened.

Table 5.1. Examples of the target word manipulation. Sentence frames included an identical preview, a homophone preview, an orthographic control preview, or a random preview.

	Example sentence
Identical preview	`Andrew sat on the` *`beach`* `watching the sunrise.`
Homophone preview	`Andrew sat on the` *`beech`* `watching the sunrise.`
Orthographic control	`Andrew sat on the` *`bench`* `watching the sunrise.`
Random preview	`Andrew sat on the` *`jfzrp`* `watching the sunrise.`

5.2.4 Off-line measures of reading ability and IQ

Similarly to the previous experimental chapters, all participants completed a range of offline tests (see Chapter 2 for further details about offline testing). IQ was measured using two subtests of the Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler, 1999); i) the vocabulary subtest, ii) the matrix reasoning subtest. In support of Experiment 1 (detailed in Chapter 3), the TOWRE was selected to explore reading ability for adults as it is formed of two parts: the sight word efficiency test and the phonemic decoding efficiency test, which together provide an overall word reading efficiency standard score for each participant. For both subtests, participants are required to read aloud as many items as possible within 45 seconds. The sight word efficiency subtest is a list of real words and the phonemic decoding efficiency subtest is a list of pseudowords. In addition to the TOWRE, supplementary tests were administered to allow for further exploration of phonological difficulties in adults with dyslexia. Specifically, the Comprehensive Test of Phonological Processing – Second Edition (CTOPP-2; Wagner, Torgen, Rashotte, & Pearson, 2013) was selected to examine phonological processing. The CTOPP-2 provides a phonological awareness composite score based upon 3 subtests: an elision task, word blending and finally phoneme isolation. Within the elision task participants are presented with a word and asked to say the word with one of its sounds deleted. For example, "Say the word blend without the /l/". This tests their ability to remove phonological segments from spoken words to form other words. Word blending requires the individual to listen to a number of individual phonemic sound components that make up a word, and to combines the sounds to form the word. Word blending tests the ability to synthesize sounds to form words. Finally, phoneme isolation requires the participant to identify the first and the last sound of a word. This task examines the ability to isolate individual sounds within words. Together these provide a phonological awareness composite score for each participant, which is a specific indication of the individuals' awareness of and access to the phonological structure of oral language.

The CTOPP-2 also provides subtests for RAN, so the CTOPP-2 was also used to measure RAN for both letters and numbers. Again, RAN requires participants to rapidly name either an array of letters or an array of numbers. The time taken to name all these items and the accuracy of which it is done provides a score that is then standardised based on age. The CTOPP provides a RAN composite score based upon the results of RAN letters and RAN numbers. This composite score is an indication of the participant's ability to efficiently retrieve phonological information from long-term memory and articulate that information, thus it is an indication of how well individuals can integrate both orthographic and phonological information.

5.2.5 Procedure

Participants sat in front of a computer screen with their head positioned in a forehead restraint and chin rest to minimise head movements during the eye movement recording. They were instructed to read the sentences silently for comprehension and to press a button on a gamepad once they had finished reading. A 3-point calibration was conducted prior to the experimental trials and selected due to the horizontal nature of single line sentences; an accurate calibration was accepted when the average errors in the validation were below 0.2° of visual angle. Calibrations were confirmed throughout the experiment and repeated when required. Each trial began with a gaze contingent box (a small black square) presented on the left hand side of the screen, positioned so that the initial letter of the sentence occupied the same location. Once the participant had fixated the square for 250ms, the sentence appeared on the screen. Participants then read the sentence silently and terminated the trial with a button press. The first 10 sentences presented were practice trials and were excluded from the analysis. After 25% of the experimental sentences a "yes/no" comprehension question appeared; participants were required to press a corresponding button to answer the question.

5.2.6 Statistical analysis

As discussed in Chapter 2, prior to the analysis, fixations less than 80ms were either merged into nearby longer fixations or excluded and fixations more than 800ms were excluded from the data set (3.37 % of fixations). Additional trials were excluded based upon the following criteria; 1) when the boundary was triggered prior to a saccade being made across the boundary, 2) when the display change completed more than 10ms after a fixation landing on the target word, 3) when the end of a saccade briefly crossed the boundary but the successive fixation remained in a position before the boundary, 4) when participants blinked on either the pre-target or target word, 5) when the participants skipped either the pre-target or target word. In total 1007 trials were removed from the analyses (34.21 % of the dataset), whilst this figure is rather high for data exclusions (typically studies report to exclude up to approximately 30% of the dataset; Chace et al., 2005; Johnson et al., 2007), data were excluded similarly across groups and conditions.

5.3 Results

Similarly to previous chapters, analyses were conducted for both global and local eye movement measures. Global measures refer to results from all of the fixations within the sentence whereas local measures were based solely on the eye movements that occurred on the target word (see Chapter 2 for discussion). In support of the previous chapters, both the global and local data were analysed using LMMs (see Chapter 2 for further discussion on the use of LMMs) using the lme4 package (version 1.1.12) in R (version 3.3.1). For global analysis, reading group was the fixed factor for all models. For local analysis, both reading group and preview condition were fixed factors for all models. Participants and items were specified as random effects for both global and local analyses. For each dependent measure, a "full" random structure was implemented including all varying intercepts and slopes of the main effects and their interaction (maximal random effects structure as suggested by Barr et al., 2013). If the "full" model failed to converge, or there were too many parameters to fit the data (as indicated by correlations of 0.99, 1, -0.99 or -1 in the random structure), the random structure was systematically trimmed (first by removing correlations between random effects, and if necessary also by removing their interactions). Successive difference contrasts were used for preview condition (comparing identical previews and homophone previews, followed by homophone previews and orthographic control previews, finally, orthographic control previews compared to random previews). Treatment contrasts were used for Reading group with Skilled Readers (SR) set as the baseline. For each contrast, beta values (b), standard error (SE) and t or z statistics are reported. Fixation time analyses were carried out on log-transformed models to increase normality and count data were analysed using generalised linear mixed models following a Poisson distribution (GLMMs).

In line with Chace et al. (2005), the local data were analysed in two ways. Therefore, in addition to the LMM analysis (where reading group was treated as a categorical variable), regressions were conducted on the difference between homophone previews and orthographic control previews, using the phonological composite score as a continuous variable to plot reading skill.

5.3.1 Eye tracking comprehension questions

The mean accuracy in comprehension scores was 92.93% correct for dyslexic readers and 95.92% for skilled adult readers, with no significant difference in scores for the two groups, $t(44)= -1.52$, $p=.134$. Thus, both dyslexic and non-dyslexic readers were able to read these sentences in order to correctly respond to the comprehension questions

5.3.2 Off-line measures of reading ability and IQ

Mean scores and statistical analyses for the offline tests are presented in Table 5.2. There were no significant differences in the IQ scores of the two groups. However, the adults with dyslexia scored significantly lower on the TOWRE and the RAN composite score compared to the skilled adult readers. Scores for the phonological composite score followed a similar trend in which dyslexic readers had lower scores compared to skilled adult readers, however, this difference was only marginally significant.

5.3.3 Global measures

The following global measures were included; total sentence reading time, average saccade amplitude, average forward and regressive fixation duration, and total number of forward and regressive fixations per sentence (See Table 5.3 for means and Table 5.4 and Table 5.5 for model outputs). Forward and regressive fixations were classified based upon the previous saccade direction (fixations preceded by a rightward saccade are considered forward fixations and fixations preceded by a leftward saccade are referred to as regressive fixations).

Total reading time: There was a main effect of reading group whereby dyslexic readers had significantly longer total reading times than the skilled readers.

Saccade amplitude: There were no significant differences in saccade amplitude for dyslexic readers compared to skilled readers.

Forward and regressive fixation durations: For forward fixation duration, there was a marginally significant effect of reading group where dyslexic readers had longer first fixation durations compared to the skilled adult readers. Regressive fixation duration showed a similar pattern, there was a significant effect whereby dyslexic readers showed longer regressive fixation durations than skilled readers.

Forward and regressive fixation counts: Dyslexic readers made significantly more forward and regressive fixations compared to the skilled readers.

Table 5.2. Mean scores and statistical analysis for the offline tests for adults with and without dyslexia. Standard scores are provided for IQ, the TOWRE, phonological composite score, and RAN composite score. Standard deviations are shown in parentheses.

	Dyslexic Readers	Skilled Readers	t-test result
IQ	108.83 (11.38)	112.30 (10.85)	$t(44) = -1.06$, $p = .294$
TOWRE	84.00 (12.12)	100.04 (11.92)	$t(44) = -4.53$, $p < .001$ ***
Phonological Composite	92.70 (14.80)	100.43 (13.68)	$t(44) = -1.84$, $p = .072$
RAN Composite	78.83 (20.29)	99.22 (14.15)	$t(44) = -3.95$, $p < .001$ ***

Table 5.3. Average global reading measures. Total reading time (ms), saccade amplitude (degrees), average fixation duration (ms) and number of fixations, for adults with dyslexia (DR) and skilled adult readers (SR).

	Total Time		Saccade Amplitude		Fixation Duration				Fixation Count			
					Forward		Regressive		Forward		Regressive	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
Dyslexic readers	5241	3044	2.57	0.72	238	46	227	65	12.90	5.81	4.54	3.88
Skilled readers	3461	1676	2.69	0.67	222	37	212	70	9.97	3.49	2.48	2.38

Table 5.4. Model output for LMMs conducted for global reading measures of total reading time (ms), saccade amplitude (degrees), average forward fixation duration (ms) and average regressive fixation duration. Significant t values ($|t| \geq 1.96$) are marked in **bold**.

	Total Time			Average saccade amplitude			Forward fixation duration			Regressive fixation duration		
	b	SE	*t*	*b*	SE	*t*	*b*	SE	*t*	*b*	SE	*t*
Intercept	8.07	0.07	**111.32**	0.97	0.04	**23.23**	5.38	0.03	**184.06**	5.29	0.03	**187.85**
Dyslexic readers	0.38	0.10	**3.75**	-0.05	0.06	-0.91	0.08	0.04	1.95	0.10	0.04	**2.57**

Table 5.5. Model output for GLMMs conducted for global reading measures of forward fixation count and regressive fixation count. Significant z values (|z| ≥ 1.96) are marked in **bold**.

	Forward fixation count			Regressive fixation count		
	b	SE	*z*	*b*	SE	*z*
Intercept	2.27	0.05	**44.89**	0.73	0.12	**5.96**
Dyslexic readers	0.24	0.07	**3.55**	0.60	0.17	**3.51**

5.3.4 Local measures

The following measures were analysed for the embedded target words; first fixation duration, single fixation duration, go-past time, total reading time, fixation count and landing position. First fixation duration is the duration of the initial fixation on the target word. Single fixation duration represents those fixations for which the reader made only one fixation on the target word during first pass. Gaze duration is the sum of fixation durations on the target word before the reader leaves that word. Go-past time is the sum of fixation durations on the target word from when a reader first fixated that word until their first fixation to the right of that word (including any regressions made before moving forward past the target word). Total time is the sum of all fixations that occur on the word throughout the whole trial (including any regressive fixations). Landing position is the character location of which the eye fixates. Table 5.6 provides the mean results for first fixation duration, single fixation duration, gaze duration, total reading time and fixation count across reading group and preview condition. Table 5.7 provides the details of the LMM outputs.

5.3.4.1 LMM analysis

First fixation duration: For first fixation duration there was no significant main effect for group. There was, however, a main effect of preview condition in which identical previews received shorter first fixations compared to homophone previews. There was no significant benefit of homophone previews compared to orthographic control previews. Finally, there was a benefit in which first fixation durations were shorter for orthographic control previews compared to random string previews. None of the interactions were significant.

Single fixation duration: In single fixation duration there was a similar pattern to that of first fixation duration. There was no significant main effect for group. There was, however, a main effect of preview condition in which identical previews received shorter first fixations compared to homophone previews. Again, there was no significant benefit of homophone previews compared to orthographic control previews. Finally, there was a marginally significant benefit in which first fixation durations were shorter for orthographic control previews compared to random string previews. None of the interactions were significant (see Figure 5.1).

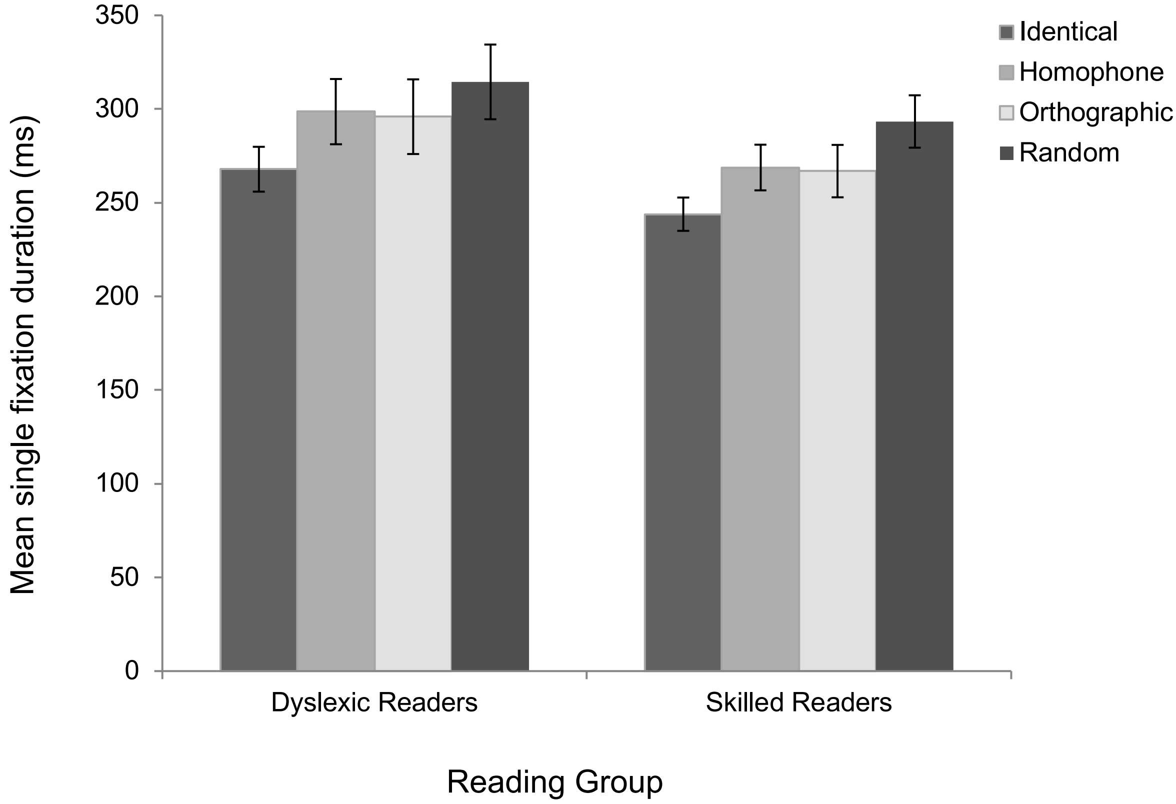

Figure 5.1. Mean single fixation durations for dyslexic readers and skilled readers across identical previews, homophone previews, orthographic control previews, and random previews. Error bars show standard error in each preview condition.

Gaze duration: For gaze duration, there was a marginal main effect for group in which dyslexic readers had longer gaze durations than skilled adult readers. Similarly to both first and single fixation duration, there was a main effect of preview condition in which identical previews received shorter first fixations compared to homophone previews. Again, there was no significant benefit of homophone previews compared to orthographic control previews. Finally, there was a significant benefit in which first fixation durations were shorter for orthographic control previews compared to random string previews. Again, none of the interactions were significant.

Go-past time: In go-past time, there was a significant main effect of group in which dyslexic readers had longer go-past times compared to skilled adult readers. There was no significant difference between the go-past times for identical previews and homophone previews. Similarly, there was no significant difference between the go-past times for homophone previews compared to orthographic control previews. Finally, there was a significant benefit in which go-past times were shorter for orthographic control previews compared to random string previews. None of the interactions were significant.

Total reading time: In total reading time, there was a significant main effect of group in which dyslexic readers had longer total reading times compared to skilled adult readers. There were, however, no effects for any of the preview condition contrasts and none of the interactions were significant.

Landing position: There were no significant effects of reading group or preview condition on landing position. There were no significant interactions.

Fixation count: For fixation count, there was a significant main effect of group in which dyslexic readers made more fixations compared to skilled adult readers. There were, however, no differences in fixation count for any of the preview condition contrasts. In addition, none of the interactions were significant.

5.3.4.1 Regression analysis

In addition to conducting LMMs to explore the effects of preview condition and reading group, additional regression analysis was conducted for the difference values between the homophone preview condition and the orthographic control preview condition. Such analysis is similar to that conducted by Chace et al. (2005), however, in the current study the difference values were regressed on phonological composite scores rather than Nelson Denny percentile ranks. Phonological composite scores did not predict the difference between homophone and orthographic control preview benefits for any of the measures (first fixation duration, single fixation duration, gaze duration, go-past time, and total time). See Table 5.8 for the results.

Table 5.6. Mean first fixation duration, single fixation duration, gaze duration, go-past time, total reading time, fixation count and landing position for the target word, as a function of preview condition and reading group. Standard deviations are shown in parentheses.

	Identical	Homophone	Orthographic	Random
First fixation duration (ms)				
Dyslexic	261 (102)	285 (116)	283 (112)	300 (130)
Skilled reader	239 (77)	262 (98)	259 (90)	285 (105)
Single fixation duration (ms)				
Dyslexic	266 (102)	294 (115)	289 (111)	321 (132)
Skilled reader	244 (78)	272 (99)	270 (89)	297 (103)
Gaze duration (ms)				
Dyslexic	304 (146)	344 (165)	321 (141)	359 (177)
Skilled reader	272 (102)	300 (126)	298 (114)	323 (119)
Go-past time (ms)				
Dyslexic	433 (360)	496 (410)	479 (427)	631 (672)
Skilled reader	329 (188)	364 (248)	356 (207)	402 (243)
Total time (ms)				
Dyslexic	466 (342)	501 (304)	532 (445)	554 (369)
Skilled reader	354 (198)	381 (226)	386 (177)	418 (232)

Table 5.6 continued.

	Identical	Homophone	Orthographic	Random
Landing position (characters)				
Dyslexic	2.95 (1.28)	2.87 (1.37)	2.92 (1.33)	2.79 (1.33)
Skilled reader	2.88 (1.33)	2.85 (1.42)	2.99 (1.51)	2.82 (1.37)
Fixation count				
Dyslexic	1.86 (1.25)	1.91 (1.08)	2.05 (1.60)	2.12 (1.42)
Skilled reader	1.55 (0.83)	1.55 (0.89)	1.58 (0.78)	1.62 (0.89)

Table 5.7. Model output for LMMs conducted for local reading measures of first fixation duration (ms), single fixation duration (ms), gaze duration (ms), go-past time (ms), total reading time (ms) and landing position (characters) on identical previews (IP), homophone previews (HP), orthographic control previews (OP), and random previews (RP). Significant t values (≥ 1.96 of standard error, SE) are marked in **bold**.

	First fixation duration			Single fixation duration			Gaze duration			Go-past time		
	b	SE	*t*	*b*	SE	*t*	*b*	SE	*t*	*b*	SE	*t*
Intercept	5.49	0.04	**152.41**	5.53	0.4	**144.45**	5.62	4.10	**137.10**	5.75	0.06	**100.52**
IP vs HP	0.06	0.03	**2.00**	0.08	0.03	**2.61**	7.66	3.21	**2.38**	0.07	0.04	1.55
HP vs OP	-0.001	0.03	-0.12	0.01	0.04	0.23	1.17	3.18	0.37	0.02	0.05	0.37
OP vs RP	0.09	0.04	**2.37**	0.09	0.05	1.92	8.73	3.19	**2.74**	0.12	0.05	**2.56**
Dyslexic readers	0.08	0.05	1.60	0.08	0.05	1.44	9.60	5.64	1.70	0.26	0.08	**3.27**
IP vs HP: Dyslexic readers	0.02	0.04	0.35	0.02	0.04	0.44	5.47	4.57	1.20	0.08	0.06	1.36
HP vs OP: Dyslexic readers	0.003	0.05	0.07	-0.03	0.05	-0.52	-6.84	4.57	-1.50	-0.07	0.07	-0.97
OP vs RP: Dyslexic readers	-0.06	0.05	-1.12	-0.02	0.07	-0.26	9.86	4.59	0.22	0.11	0.07	1.60

Table 5.7 continued.

	Total time			Landing position			Fixation count		
	b	SE	*t*	*b*	SE	*t*	*b*	SE	*t*
Intercept	5.83	0.06	**96.81**	2.92	0.12	**25.47**	0.43	0.05	**8.04**
IP vs HP	0.06	0.04	1.62	0.05	0.14	0.37	0.01	0.07	0.21
HP vs OP	0.05	0.05	0.99	0.10	0.13	0.75	0.02	0.07	0.23
OP vs RP	0.07	0.06	1.19	-0.21	0.14	-1.52	0.03	0.07	0.39
Dyslexic readers	0.24	0.08	**2.94**	-0.001	0.15	-0.01	0.22	0.07	**3.02**
IP vs HP: Dyslexic readers	0.03	0.06	0.62	-0.11	0.19	-0.59	0.01	0.10	0.07
HP vs OP: Dyslexic readers	-0.04	0.07	-0.61	-0.01	0.18	-0.08	0.05	0.10	0.05
OP vs RP: Dyslexic readers	0.01	0.08	0.12	0.03	0.17	0.18	0.02	0.10	0.18

Table 5.8. Results of the regression analysis conducted on the difference values of homophone previews compared to orthographic control previews regressed on phonological composite scores. Results are reported for local reading measures of first fixation duration (ms), single fixation duration (ms), gaze duration (ms), go-past time (ms) and total reading time (ms).

	R^2	Adj. R^2	*F*	*p (F)*	Constant	β_1	*t*	*p (t)*
Phonological composite score								
First fixation	.002	-.021	.09	.766	-18.33	.17	0.30	.766
Single fixation	.001	-.021	.06	.814	-15.97	.14	0.24	.814
Gaze duration	.028	.005	1.25	.270	-92.48	.81	1.12	.270
Go-past time	.002	-.021	.08	.775	-43.87	.37	0.29	.775
Total time	.022	<.001	.99	.325	-123.85	1.47	0.99	.325

5.4 Discussion

The aim of the current study was to examine phonological parafoveal processing in dyslexic reading; specifically, to examine whether adults with dyslexia gain benefit from phonological parafoveal processing in addition to orthographic parafoveal processing. The pattern of results indicated that both dyslexic and skilled adult readers gained preview benefit during reading; for both reading groups, orthographic control previews provided greater preview benefit compared to random previews, and identical previews provided greater preview benefits compared to homophone parafoveal previews. There was, however, no evidence of a significant benefit of homophone previews compared to orthographic control previews for either of the reading groups. Therefore, in the current study, there was no evidence that phonological information provides further preview benefit compared to orthographic information. Finally, in regard to foveal eye movement patterns, dyslexic readers required longer viewing durations and made more fixations than skilled adult readers.

Similarly to the previous experiments reported in this thesis (see Chapter 3 and Chapter 4), and in support of previous research into parafoveal processing during the RAN task (Jones et al., 2013; Yan et al., 2013), the current results provide evidence for parafoveal processing during reading for dyslexic readers. Notably, during first fixation duration, single fixation duration and gaze duration, both dyslexic and non-dyslexic readers showed a benefit of orthographic control previews compared to random previews. These two types of preview manipulations varied in letter identity across the full length of the word (e.g. compare *bench* to *jfzrp*). Therefore, differences in these preview manipulations demonstrate that both reading groups were encoding orthographic information from parafovea. Indeed, both dyslexic and non-dyslexic readers appear to encode letter identity from the parafoveal word in order to aid lexical identification, and having the correct preview for the first two letters is beneficial compared to having an incorrect parafoveal preview for all letters of the word. Such finding supports previous research demonstrating orthographic parafoveal processing for skilled readers (Johnson et al., 2007; Pagán et al., 2016; Tiffin-Richards & Schroeder, 2015), and, also supports the findings shown for dyslexic readers in both Chapter 3 and Chapter 4. Similarly to the findings in previous chapters of this thesis, dyslexic readers were able to allocate their attention to the parafovea in order to encode orthographic information during silent sentence reading.

In addition to demonstrating a preview benefit for orthographic control previews compared to random previews, both dyslexic and skilled readers showed a benefit of identical previews compared to homophone previews and this occurred within first fixation duration, single fixation duration and gaze duration. This finding is somewhat contrary to previous studies which demonstrated that when the first two letters of the previews overlap, preview benefits for skilled adult readers are close to that obtained when the previews were identical (Balota et al., 1985; Rayner et al., 1980). Such finding is also contrary to Pollatsek et al. (1992) who found that, for skilled adult readers, there was no difference in the preview benefits gained from identical previews and homophone previews. The current pattern of results do, however, support that of Choi and Gordon (2014) who also found skilled readers showed a greater preview benefit from identical previews compared to homophone previews. Thus, whilst there are mixed findings within the literature, the current findings suggest that viewing an identical parafoveal preview provides greater benefit, and therefore greater lexical activation, compared to viewing a homophone parafoveal preview even though there was a large amount of orthographic and phonological overlap (for orthographic information this was at least the first two letters, and, phonology was matched across the whole word).

The finding that both reading groups showed greater preview benefit for identical previews compared to homophone previews indicates that both groups were able to allocate their attention to the beginning of the parafoveal word in order to encode the letter identities of the initial similar letters, but, also allocate their attention towards the middle or latter end of the word to encode letter identity for the letters that differ across the preview manipulations (e.g. compare *beach* to *beech*). In fact, it is the letter identity encoding for the middle or latter letters that provides the additional preview benefit that occurs for identical previews compared to homophone previews (this will be discussed in further detail later within this section). Thus, whilst both identical and homophone previews have the same phonological form, previewing the correct orthographic representation of the word provides greater lexical activation and increases the preview benefit effects for both skilled and dyslexic readers. Although this specific comparison cannot determine if either group of readers are in fact encoding phonological information from the parafovea, these results suggest that perhaps encoding phonology is not enough to provide optimal preview benefit and that orthographic information is also important.

Further to providing evidence for orthographic parafoveal processing, the current study aimed to explore whether dyslexic readers gained parafoveal preview benefit from phonological information. Contrary to previous studies with skilled adult readers (Ashby & Rayner, 2004; Ashby et al., 2006; Chace et al., 2005; Liu et al., 2002; Miellet & Sparrow, 2004; Pollatsek et al., 1992; Rayner et al., 1995; Sparrow & Miellet, 2002; Tsai et al., 2004), neither reading group showed a benefit of homophone previews compared to orthographic control previews. It is, therefore, unclear as to whether skilled readers or dyslexic readers gain additional preview benefit from encoding phonological information parafoveally. As discussed in the introduction, phonological preview benefits are typically hard to identify, and, there are a number of studies that have been unable to provide evidence for phonological parafoveal preview benefits (Choi & Gordon, 2014; Lee et al., 1999; Lee et al., 1999; Rayner et al., 1980).

In order to increase the likelihood of finding phonological parafoveal preview benefits, the current study purposely used the stimuli from Chace et al. (2005) who were able to demonstrate phonological parafoveal preview benefits for skilled adult readers during reading. Furthermore, data were collected from an increased sample size to further aid in establishing the effects. Contrary to the predictions and the results of Chace et al. (2005), however, skilled adult readers did not show an increased preview benefit from homophone previews compared to orthographic control previews within the current study. Whilst it was predicted that dyslexic readers would not demonstrate an increased preview benefit for homophone previews compared to orthographic control previews, because skilled readers did not demonstrate the pattern of results previously found with this stimuli, it is impossible to draw conclusions about dyslexic phonological parafoveal processing.

As proposed by previous researchers (Choi & Gordon, 2014; Pollatsek et al., 1992), a lack of evidence for phonological parafoveal processing in the skilled adult readers might be due to the high degree of orthographic overlap between homophone and orthographic control previews. The similarity between the previews often makes it difficult to establish a difference and the effects are typically very small in duration. It is, however, important to note that Chace et al. (2005), were able to establish an effect with the same set of stimuli, and within the current results there was a significant difference in the preview benefit of identical previews compared to homophone previews. This finding is important because identical previews (e.g. *beach*) and homophone previews (e.g. *beech*) shared the same level of orthographic overlap as homophone previews and orthographic control previews (e.g. *bench*). As such, it is unlikely that orthographic overlap is the primary cause of the lack of evidence for phonological preview benefit demonstrated within the current study.

Another possible explanation for the lack of evidence supporting phonological parafoveal preview benefits in skilled adult reading may be due to the word frequency scores used within the current study. Whilst the stimuli were piloted with thirteen native British English speakers, to make sure they were understandable and coherent, the word frequency scores originated from the Chace et al. (2005) study. Within their experiment, Chace et al. (2005) used word frequency scores from the Francis and Kučera (1982) database to determine the frequency of the pre-target and target word. To be specific, the word frequency of the target word was matched across three of the preview conditions (identical previews, mean: 41, SD: 72;

homophone previews, mean: 45, SD: 90; and orthographic control previews, mean: 45, SD: 76). Whilst the Francis and Kučera (1982) word frequency scores were previously regularly used in samples of British English readers (e.g. Ashby, Rayner, & Clifton, 2005; Kirkby et al., 2013; White et al., 2005a; 2005b), such database is now often considered to be a somewhat out-of-date word frequency database (Balota, Cortese, Sergent-Marshall, Spieler, & Yap, 2004; Brysbaert & New, 2009; Burgess & Livesay, 1998; Zevin & Seidenberg, 2002), and for British English readers the preference has moved toward the British National Corpus (BNC). When using the BNC values of word frequency, the pre-target words remain, on average, low frequency words (mean: 31.34 per million, SD: 51.96). However, for the target words, there are differences in the frequency scores across the preview manipulations. Specifically, using the BNC, word frequency scores are as follows: identical previews (mean: 38.25 per million, SD: 72.14), homophone previews (mean: 52.76 per million, SD: 141.55), orthographic control previews mean: 71.79 per million, SD: 200.81). Thus, whilst the target word stimuli were well matched for US English readers (using Francis & Kučera, 1982), there was much greater variation in frequency across target words for British English readers (when using BNC).

Whilst the differences in word frequency across the target word preview manipulations are perhaps rather small, considering that word frequency scores in the BNC can range up to 68,954 for words such as “the”, any additional noise that is not controlled for may impact the ability to detect already temperamental phonological parafoveal preview effects. It may be the case that when target words are less frequent words, they require additional attentional resources to parafoveally process (Henderson & Ferreira, 1990). In fact, the onset of phonological encoding occurs later in time compared to the onset of orthographic encoding, and orthographic codes are activated prior to phonological codes (Lee et al., 1999; Lee et al., 1999). Therefore, it is possible, that words with lower word frequency scores are orthographically encoded, but phonological encoding is limited due to restrictions in attention. Consequently, phonological parafoveal processing may be limited during occasions when the target word is lower in word frequency.

Such reasoning would explain why identical previews showed greater preview effects than homophone previews; if these words require increased attentional resources, due to being lower frequency words, phonological information may not be encoded parafoveally, thus the identical preview provides greater orthographic overlap and therefore larger preview benefit compared to homophone previews. Furthermore, more frequent words, such as the orthographic control previews, may benefit from some level of phonological parafoveal processing. This would then eradicate any difference between the homophone and orthographic control preview benefits (as homophone previews are orthographically similar), and perhaps provide slightly more preview benefit for orthographic control previews, which may have received some level of phonological encoding. Therefore, the differences in frequency scores across the target word preview manipulations may explain why the current study did not find evidence for phonological parafoveal preview benefits. As such, it is still unclear as to whether dyslexic readers can encode phonological information parafoveally during reading.

Whilst the current study was unable to determine whether dyslexic readers can encode phonological information from the parafovea, there are still a number of interesting findings from the current results. Notably, in contrast to findings from the poor readers in the study by Chace et al. (2005) who did not show any evidence of parafoveal processing, the current results show that dyslexic readers do gain parafoveal preview benefit during reading. Thus, it is possible that dyslexic readers and the poor readers selected within Chace et al. (2005) represent different subsets of reading difficulty; dyslexic readers and poor comprehenders have been identified as separate samples of reading disability (Cain et al., 2000; Cain, 2010; Hulme & Snowling, 2009; Nation et al., 1999; Nation & Snowling, 1998b; Snowling & Hulme, 2012; Stothard & Hulme, 1995). Furthermore, in contrast to Chace et al. (2005) who found the Nelson-Denny percentile rank scores predicted phonological preview benefits, the phonological composite score (from the CTOPP) was not found to predict phonological preview benefits in the current sample. It is, therefore, possible that the reading difficulties as identified using the Nelson Denny test (using tests of vocabulary and reading comprehension, which rely much more upon extracting meaning from language rather than phonological decoding) provide a greater indication of phonological parafoveal processing than the phonological composite score from the CTOPP, which is an overall indication of the individuals awareness of, and access to, the phonological structure of oral language. Parafoveal processing is dependent on attention (Miellet et al., 2009); therefore phonological parafoveal processing may rely heavily upon attentional resources rather than decoding as an isolated measure. Such possibility, however, would need to be explored thoroughly with further empirical research.

Another interesting finding from the current study demonstrates that dyslexic readers showed the ability to parafoveally process orthographic information even when the pre-target word was a low frequency word. In both Experiment 1 and Experiment 2 of this thesis (reported in Chapters 3 and 4), dyslexic readers showed the ability to parafoveally process orthographic information, but, during these initial studies, the pre-target word was purposely manipulated to be a high frequency word. It has been proposed that dyslexic readers have limited attentional resources and as such, when foveal demands are high (as the case with a low frequency pre-target word), dyslexic readers have less attentional resources to allocate to parafoveal processing. Nonetheless, as demonstrated within the current study, dyslexic readers were able to allocate their attention to the parafoveal word to encode orthographic information during reading, even when the pre-target word was a low frequency word with increased foveal processing demands. Thus, for dyslexic readers, the attentional resources required for parafoveal processing may not always be limited by foveal demand during reading (however, note that this was not explicitly tested within the current study so firm conclusions cannot be drawn). This suggestion is, however, further supported by the finding that dyslexic readers can encode parafoveal information from the middle or latter end of the target word even when foveal demand is increased.

Recall that dyslexic readers gained increased preview benefit from identical previews compared to homophone previews. Interestingly, both identical previews and homophone previews typically had the same two initial letters, thus the manipulation only became apparent from the middle of the word onwards (e.g., *beach*, *beech*). To clarify, in the first two experiments of this thesis, parafoveal manipulations were kept to the initial letters of the word to ensure that dyslexic readers would show an impact of the manipulation if their attention was restricted. Therefore, whilst preview effects during orthographic parafoveal processing were reported in Chapters 3 and 4, it was impossible to be certain whether parafoveal processing might occur for letters in the middle or end of the word. In addition, the initial letters are intrinsically more important to lexical identification, and, manipulating the initial letters often causes greater disruption to lexical identification than when letter manipulations occur internally within a word (Johnson & Dunne, 2012; Johnson & Eisler, 2012; Johnson et al., 2007; Tiffin-Richards & Schroeder, 2015; White et al., 2008). It was unclear whether dyslexic readers would gain parafoveal preview benefits from internal letters of a word, since they do not hold the same intrinsic importance, and restrictions in attention allocation may have prevented dyslexic readers from gaining preview benefits from the middle or end of the parafoveal word.

The current study showed that dyslexic readers do gain benefit of identical previews compared to homophone previews, consequently demonstrating that they can allocate their attention to encode information from not only the beginning letters but also the middle letters of the parafoveal word. This indicates that dyslexic parafoveal preview benefits are not purely a function of disrupting the initial letters of the parafoveal word, and dyslexic readers do gain preview benefits from internal letters of the parafoveal word. In fact within the current study, dyslexic readers demonstrated the ability to allocate their attention to the middle letters of the parafoveal word, even when foveal load was increased (due to the low frequency pre-target word). Such findings might suggest that dyslexic readers did not have difficulty in processing these sentences and, therefore, had adequate attentional resources to allocate to parafoveal processing during reading. Such explanation is, however, contrary to the finding that dyslexic readers did show foveal eye movement patterns indicative of reading difficulty. It is possible that dyslexic readers were unable to restrict their attentional resources accordingly during parafoveal processing. Clearly, dyslexic readers can allocate their attention to the parafovea; however, they may have difficulty in selecting the correct information on which to focus their attention (Boden & Giaschi, 2007). In which case they may allocate attention to both foveal and parafoveal information within their perceptual span, but not have developed the correct attentional gradient (Whitney & Cornelissen, 2005) to prioritise encoding of foveal information by restricting attention allocation. Such a suggestion is in line with the findings that dyslexic readers may have more widely distributed attention leading to increased parafoveal processing compared to non-dyslexic readers (Geiger & Lettvin, 1987; Geiger et al., 1992; Lorusso et al., 2004), and results that demonstrate dyslexic readers show confusability when encoding foveal and parafoveal information during RAN (Jones et al., 2008; 2009; 2013). In this suggestion, dyslexic readers struggle to restrict their attentional focus and encode too much information, which then competes for lexical activation. Indeed, this may help to explain why dyslexic readers have longer fixation durations and make more fixations.

To conclude, in support of previous research into dyslexic eye movements during reading (Kirkby et al., 2008; 2011) and of Chapter 3 of this thesis, the present study found the usual effects of reading ability on eye movement behaviour. Specifically, dyslexic readers required longer viewing durations than the skilled adult readers and this occurred at both global (average regressive fixation duration and total reading time) and local levels (gaze duration, go-past time, and total reading time). Dyslexic readers also required more forward fixations and more regressive fixations than skilled adult readers at a global level and local level. Whilst the differences in first fixation duration and single fixation duration were not significantly different, there was a trend to support the usual effects, where dyslexic readers had longer fixations than skilled readers. Finally, there were no significant differences in the landing positions of dyslexic readers and skilled adult readers. Altogether, the pattern of results demonstrate that the current sample of dyslexic readers showed reading difficulties compared to the sample of skilled adult readers; indeed, their eye movement behaviour was indicative of the dyslexic readers' difficulties with linguistic processing during reading.

In sum, whilst the present study aimed to explore phonological parafoveal processing in adults with dyslexia, neither adults with dyslexia nor skilled adult readers showed benefit of homophone previews compared to orthographic control previews. It is, therefore, unclear as to whether dyslexic readers can encode phonological information from the parafovea. In addition, the CTOPP (which provided an indication of the readers' awareness of and access to phonology) did not predict phonological parafoveal preview benefits, suggesting that the ability to gain phonological parafoveal preview benefits may be driven from additional factors such as attention. The current findings did, however, provide additional evidence for dyslexic readers' ability to encode orthographic information from the parafovea during reading. In fact, dyslexic readers were able to allocate their attention to the middle of the parafoveal word to extract orthographic information, even when the pre-target word was a low frequency word. Within the current study, dyslexic readers' attention was not restricted by the increased foveal demand and, thus, they did not show deficits in attention allocation for orthographic processing.

5.0 Chapter summary

Further to the previous experimental chapters, which explored orthographic parafoveal processing for readers with dyslexia, this chapter details the exploration of phonological parafoveal processing for dyslexic adults. Similarly to the previous experiments in this thesis and contrary to the findings of Chace et al. (2005), dyslexic readers showed preview benefits from orthographic information during reading. There were, however, no significant effects to indicate phonological parafoveal processing during reading for either skilled readers or dyslexic readers. As such, the current study does not allow for conclusions to be made on dyslexic phonological parafoveal processing. The final chapter provides discussion and conclusions based upon the findings from all three experiments reported in this thesis.

Chapter Six: Discussion

6.0 Chapter overview

This final chapter provides an overview of the thesis, including: the aims introduced in the initial chapter, discussion of the main findings, challenges within the current research and, finally, future research directions.

6.1 Recap of thesis

Reading plays a vital role in modern society; much of the teaching provided at school requires children to read and approximately 90% of all careers require literacy skills (Lenhard et al., 2005). Whilst most children learn to read with relative ease, between 5-17% of children will be diagnosed with developmental dyslexia; a lifelong reading disability that impacts their ability to learn to read (Shaywitz, 1998). Although dyslexia is one of the most common learning disabilities, there is still a lot we do not know about the cause.

Eye movements provide great insight into the moment-to-moment cognitive processes that occur during reading and, because of this, eye movement research has been highly influential in developing our understanding of skilled adult reading (Liversedge et al., 2011; Radach & Kennedy, 2013; Rayner, 1998). There is now a large body of research providing evidence for the basic characteristics of eye movements in skilled adult readers (for reviews, see Rayner, 1998, 2009) and in more recent years, researchers have started to use eye movement technology to explore reading development by collecting eye movement data with child participants (for reviews see, Blythe, 2014; Blythe & Joseph, 2011; Rayner et al., 2013).

There is, however, still a paucity of eye movement research conducted with children and adults with developmental dyslexia during reading (although, see Kirkby et al., 2011; Bellocchi et al., 2013) and specifically during parafoveal processing. This is surprising given that dyslexia has been causally linked to both phonological deficits (Snowling, 2000) and difficulties in allocating attention (Bosse et al., 2007; Valdois et al., 2004; Hari & Renvall, 2001; Vidyasagar, 1999; Whitney & Cornelissen, 2005), both of which are utilised during parafoveal processing (Schotter et al., 2012). Furthermore, whilst there is a small body of work exploring dyslexic eye movement behaviour, very few studies have compared dyslexic readers to non-dyslexic readers matched on chronological age and also non-dyslexic readers matched on reading age (Olson et al., 1991; Hyönä & Olson, 1995; Rayner, 1985a, Rayner 1985b). By comparing dyslexic children to both of these control samples, one can determine whether differences in dyslexic eye movement behaviour are specific to dyslexia, or due to a developmental lag in their ability to read. As such, the current thesis aimed to further inform theoretical accounts of dyslexia by examining foveal and parafoveal eye movement behaviour in readers with and without dyslexia.

The aims of the thesis were: 1) to provide a detailed characterisation of dyslexic eye movement patterns during silent reading, for both adults and children, 2) to determine whether dyslexic adults and children gain parafoveal preview benefits during silent sentence reading, 3) to understand what information is encoded from the parafovea during dyslexic silent sentence reading, 4) to explore the nature of the dyslexic eye movement patterns by experimentally comparing children with dyslexia to groups of typically developing children matched for chronological age, but also typically developing children matched for reading age. Thus, this thesis reports three research studies conducted to address these aims.

6.2 Summary of key findings

The thesis details three eye movement experiments examining both foveal and parafoveal processing of readers with and without dyslexia. The main findings of the research were as follows:

- In comparison to typically developing children that were matched on chronological age, dyslexic children showed eye movement patterns indicative of their linguistic processing difficulty, such as: increased fixation durations (both regressive and forward fixations), more fixations (regressive and forward fixations), shorter saccades, increased first fixation durations, single fixation durations, gaze durations, increased go-past times and total reading times.
- Dyslexic children also showed differences in eye movement behaviour compared to typically developing children that were matched for reading age. Dyslexic children made more fixations and longer regressive fixation

durations, resulting in longer gaze durations, go-past times and total reading times compared to typically developing children matched for reading age.

- Adult dyslexic readers also showed differences in eye movement patterns compared to skilled adult readers. Dyslexic adult readers made more fixations (forward and regressive) and had increased regressive fixation durations, gaze durations, go-past time and total reading times compared to skilled adult readers. Dyslexic readers also made longer forward fixation durations, first fixation durations and single fixation durations compared to skilled adult readers, although these differences were not always significant.
- Throughout all three experiments, dyslexic readers (children and adults) showed orthographic parafoveal preview benefit during reading. Experiment 1 and 2 demonstrated that adults and children encode orthographic information from at least the two initial letters of the parafoveal word. Experiment 3 demonstrated that the dyslexic adults could extend their attention further to the parafovea and gain orthographic parafoveal preview benefits from manipulations that occur after the initial two letters of the parafoveal word.
- Although orthographic parafoveal preview benefits were demonstrated in Experiment 3, there was no evidence to support phonological parafoveal preview benefits for skilled adult or dyslexic adult readers.
- Both adults (Experiment 1) and children (Experiment 2) with dyslexia were found to encode letter position information during parafoveal processing; both groups of readers demonstrated a parafoveal preview benefit when viewing identical previews compared to transposed-letter previews.
- Dyslexic adults and children did, however, show a greater reliance on letter position for lexical identification compared to their peers (skilled adult readers and typically developing children matched for chronological age). Dyslexic readers demonstrated a larger parafoveal preview benefit for identical previews compared to transposed-letter previews than their non-dyslexic peers.
- Dyslexic readers were found to encode letter identity and letter position independently during parafoveal processing, as evidenced by greater preview benefits for transposed-letter previews compared to substituted-letter previews. Thus, indicating that dyslexic readers do use a flexible letter

position encoding mechanism. Dyslexic readers did, however, show transposed-letter effects during later eye movement measures relative to their peers.

- Dyslexic children showed similar parafoveal processing abilities to the typically developing children matched on reading age; both of these poorer reading groups showed a greater dependence on letter position information (increased parafoveal preview benefit for identical previews compared to transposed-letter previews). This greater dependence on letter position information then resulted in a delayed TL effect (increased parafoveal preview benefit for transposed-letter previews compared to substituted-letter previews) relative to the typically developing children matched to the dyslexic children on chronological age.
- These difficulties in letter position encoding, however, still occurred for dyslexic adult readers who demonstrated greater dependence on letter position information and a transposed-letter effect that only occurred in later eye movement measures compared to skilled adult readers.

Thus this thesis contributes new knowledge to the field by providing the first research studies to demonstrate that dyslexic readers do gain orthographic parafoveal preview benefits during silent sentence reading, that they do encode letter identity and letter position from the parafovea, and they can encode parafoveal information from at least the middle of the parafoveal word. The above results are discussed in detail throughout the following section.

6.2 Discussion of key findings

6.2.1 Foveal processing

Throughout all three experimental chapters, dyslexic readers showed different eye movement patterns to the non-dyslexic readers. Specifically, the research in this thesis demonstrates that dyslexic readers show different eye movements compared to non-dyslexic readers of the same age. As demonstrated in Experiment 1 and Experiment 3, adult dyslexic readers showed a significant increase in fixation count (forward and regressive), increased regressive fixation durations, gaze durations, go-past time and total time compared to their non-dyslexic peers. In addition, dyslexic adults consistently showed a numerical trend for increased forward fixation duration, first fixation duration and single fixation duration compared to non-dyslexic adults. In support of the results for the adult dyslexic readers, dyslexic children also demonstrated different eye movement behaviour compared to typically developing children of the same chronological age. As evidenced in Experiment 2, dyslexic children demonstrated longer viewing durations (such as average fixation duration, first fixation duration, single fixation duration, gaze duration, go-past time, and total reading time) and made more fixations (both forward and regressive fixations) compared to typically developing children matched for chronological age.

Taken together, the results from the child data and the adult data suggest that dyslexic readers consistently demonstrate different eye movement behaviour compared to their chronological age matched peers, and this difference occurs throughout the lifespan. Indeed, as eye movements provide insight into the moment-to-moment cognitive processes that occur during reading (Liversedge et al., 2011; Radach & Kennedy, 2013; Rayner, 1998), it is generally accepted that the differences in eye movement behaviour found during reading reflects the readers ability to linguistically process text (Blythe, 2014; Häikiö et al., 2009; Kirkby et al., 2008; Rayner, 1986). The current findings, therefore, indicate that dyslexic readers demonstrate slower and more effortful lexical processing compared to their non-dyslexic peers and supports previous studies of dyslexic eye movements during reading (Biscaldi et al., 1998; De Luca et al., 2002; De Luca et al., 1999 Hatzidaki et al., 2011; Hawelka & Wimmer, 2005; Hawelka et al., 2010; Hutzler & Wimmer, 2004; McConkie et al., 1991; Rayner, 1986; Zoccolotti et al., 1999).

The finding that dyslexic readers make longer and more fixations is consistent with the Lexical Quality Hypothesis (Perfetti, 2007; Perfetti & Hart, 2001, 2002) which suggests that variation in the quality of lexical representations of words impacts upon reading skill. Within this proposal, through reading experience, readers develop high quality lexical representations allowing quick, reliable, and simultaneous access to a word's orthography, phonology, and semantics in order to achieve efficient word identification. Lexical representations that do not meet the criteria for high quality representations are considered to be low quality lexical representations and result in effortful and slow lexical identification. Indeed, due to dyslexic readers difficulties with reading, they have lower quality lexical representations compared to their non-dyslexic peers and, therefore, demonstrate differences in their eye movement behaviour. As such, dyslexic readers eye movement behaviour is considered representative of their difficulties in linguistic processing rather than a cause of their reading difficulties (Bellocchi et al., 2013; Kirkby et al., 2011; Rayner, 1986).

In addition to exploring the eye movement patterns of readers with dyslexia compared to non-dyslexic readers matched on chronological age, Experiment 2 explored the eye movement patterns of children with dyslexia compared to typically developing children matched for reading age. Although it is widely accepted that eye movement patterns are indicative of linguistic processing (Blythe, 2014; Häikiö et al., 2009; Kirkby et al., 2008; Rayner, 1986), in order to further understand the causes of dyslexic eye movement patterns, dyslexic readers need to be compared to two control groups: a group of non-dyslexic readers matched for chronological age, and, a group of non-dyslexic readers matched on reading age. This allows us to examine whether differences in eye movement and reading behaviour are explained by differences in reading ability and therefore indicative of a developmental lag in which dyslexic readers are just less experienced, poorer readers, or, whether there is specific dyslexic deficit (such as difficulty in attention allocation; Bosse et al., 2007; Valdois et al., 2004; Hari & Renvall, 2001; Vidyasagar, 1999; Whitney & Cornelissen, 2005) that impacts upon their ability to read.

As reported in Experiment 2, dyslexic children did in fact demonstrate differences in their eye movement behaviour compared to typically developing children matched on reading age. Although their individual fixation durations were similar, and therefore representative of their linguistic processing ability, dyslexic children made more fixations compared to reading age matched children. This increased fixation count then resulted in longer gaze durations, go-past times and total reading times. The finding that dyslexic children show increased fixation count compared to typically developing children matched for reading age suggests that dyslexic eye movement behaviour is not only indicative of their reading skills; there must be a specific dyslexic deficit that impacts their fixation count and occurs independently to the developmental lag in their reading development. This finding is similar to the results found for the dyslexic adult readers (Experiment 1 and 3) who did not always demonstrate significantly increased fixation durations but consistently made additional fixation durations compared to their peers.

As discussed in detail in Chapter 4, there are a number of reasons as to why dyslexic readers may make more fixations compared to non-dyslexic readers with the same reading age, and these may be due to difficulties in attention and/or the speed of processing of phonological information. One explanation for increased refixations on a word is that dyslexic readers have limitations in visual sampling. In fact, compared to non-dyslexic readers, dyslexic readers have been found to show both a reduced perceptual span (Rayner et al., 1989) and limitations in the VA span (recall the VA span corresponds to the amount of orthographic information that can be simultaneously processed when reading, see Chapter 1 for detailed discussion of the VA span; Bosse et al., 2007; Prado et al., 2007; Valdois et al., 2004). Furthermore, Prado et al. (2007) demonstrated that children who have a smaller VA span made more first-pass fixations during reading than children with a larger VA span. As such, dyslexic readers may have a specific attention deficit which means they are not able to encode enough information within one fixation and therefore need to make additional fixations. In addition, a reduced VA span has been found to occur in dyslexia independent of phonological difficulties (Bosse et al., 2007; Prado et al., 2007), thus explaining why dyslexic readers make additional fixations compared to both non-dyslexic readers matched on chronological age and non-dyslexic readers matched on reading age.

A second explanation for why dyslexic readers make more fixations compared to non-dyslexic readers is that they have difficulty in prioritising foveal information for lexical identification; whilst dyslexic readers are able to allocate their attention to the parafovea, they may do so at the expense of prioritising foveal processing. Such suggestion is in line with previous research finding that dyslexic readers have increased parafoveal processing compared to non-dyslexic readers (Geiger & Lettvin, 1987; Geiger et al., 1992; Lorusso et al., 2004). In their early work, Geiger and Lettvin (1987) briefly presented dyslexic and non-dyslexic adults with pairs of letters to identify; one at the center of eye gaze and one presented horizontally adjacent in the periphery at a variety of eccentricities. Non-dyslexic readers demonstrated a sharp decrease in the recognition rate of the peripheral letter with increasing eccentricity. Dyslexic adult readers, however, had a wider area of correct identification; they were able to correctly identify letters presented further into the periphery of the right hemifield compared to non-dyslexic readers. Such result has been supported in both dyslexic adults and children (Geiger & Lettvin, 1987; Geiger et al.,1992; Geiger, Lettvin, & Fahler, 1994; Lorusso et al., 2004; see also Facoetti et al., 2000), demonstrating that dyslexic readers have a wider distribution of attention across the visual field compared to non-dyslexics when processing small amounts of information (such as 2 individual letters).

The finding that dyslexic readers have a wider distribution of attention can be explained by lateral masking. Dyslexic readers have reduced lateral masking; they are less able to suppress parafoveal and peripheral information to avoid the effects of crowding on foveal processing (Facoetti et al., 2000; 2003; Geiger & Lettvin, 1986). Whilst there is still much debate about the causes of crowding (for a review see Gori & Facoetti, 2015), is has been argued that crowding is modulated by attention (Chen et al., 2014; He, Cavanagh, & Intriligator, 1996; Intriligator & Cavanagh, 2001; Petrov & Meleshkevich, 2011a, 2011b; Strasburger, 2005; Yeshurun & Rashal, 2010). Thus, dyslexic attention deficits may result in dyslexic readers being less able to suppress extraneous information and effectively prioritise foveal information. In fact, interventions that focus on reducing crowding by increasing inter-letter spacing show evidence for improved reading performance, particularly for those with dyslexia (Perea et al., 2012; Spinelli et al., 2002; Zorzi et al., 2012). Dyslexic readers may, therefore, make additional fixations due to difficulties in effectively allocating attention to foveal processing. In fact, this is further supported by findings demonstrating that dyslexic readers show confusability in processing foveal and parafoveal information (Jones et al., 2008; 2009; 2010; 2013). Specifically, Jones et al. (2013) found that dyslexic readers were more susceptible to orthographic confusability in the parafovea and phonological confusability in the fovea. Such a result supports the notion that dyslexic readers have difficulty in correctly mapping their attentional resources across foveal and parafoveal information (prioritising and inhibiting the correct information).

Increased fixation counts may also be explained by dyslexic readers' slow encoding of phonological information from orthographic form resulting in lexical activation taking longer. Whilst dyslexic readers and reading age-matched children have similar phonological skills, dyslexic readers may be slower to encode phonological information. Indeed, in Experiment 2, the tests used to match dyslexic children to reading-age matched children did not take into account the time taken to complete phonological processing (see Blythe et al., 2018 for a similar comparison in which pen and paper tests do not accurately reflect the eye movement behaviour during silent sentence reading). Although specific word identification models may differ on the exact processes, it is generally accepted that saccades to the next word are programmed when a level of lexical activation occurs (such as the completion of word identification, Morrison, 1984; or the completion of an early stage of lexical processing called the familiarity check which is an overall feeling of familiarity based on the word's orthographic form; Pollatsek et al., 2006; Reichle et al., 1998), and this lexical activation requires both orthographic and phonological information. Specifically, within the E-Z Reader model (Reichle et al., 1998) saccades are initially programmed when successful orthographic recognition occurs (i.e. the familiarity check, Pollatsek et al., 2006) and attention moves to *N*+1 once the word's phonology and meaning is accessed (i.e. lexical completion). Thus, if the reader can rapidly encode orthographic and phonological information, a saccade will be programmed to the next word and attention will move to *N*+1 for pre-processing. If saccade programming is still in an early labile stage when the familiarity check of word *N*+1 is completed, then the saccade programming for word *N*+1 will be cancelled and replaced by the programming of a saccade to word *N*+2. This would explain word skipping in skilled readers. If, however, the required level of lexical activation does not occur quickly enough to programme a saccade to the next word, another eye movement will be triggered to refixate the current word; preventing the eyes from staying too long on the same location without moving. Thus, if dyslexic readers are slow to encode grapheme-phoneme representations, the next eye movement may be programmed to refixate the currently fixated word in order to allow additional time for lexical processing. Indeed, Blythe et al. (2018) found that teenagers with permanent childhood hearing loss showed a delay in their processing of phonological information compared to their age matched peers, with the pseudohomophone advantage occurring only in the second fixation for hearing loss readers. Thus, less skilled readers may require additional fixations in order to encode phonological information.

The above suggestion that additional fixations may occur due to slow encoding of phonological information is supported by the phonological deficit theory (Liberman, 1973; Snowling, 1995; Snowling, 2000; Snowling & Hulme, 2012; Stanovich, 1988), where dyslexic readers have difficulty in forming grapheme-phoneme representations. This makes it more challenging for those with dyslexia to distinguish between, and thus slower to select and retrieve, the correct orthographic and phonological representations. Such delay in correctly mapping orthographic and phonological information would, therefore, impact the early lexical activation required to program a saccade to the next word. An alternative explanation is that slower lexical activation could also be explained by the SAS Hypothesis (Sluggish Attentional Shifting; Hari & Renvall, 2001; Lallier et al., 2010), which suggests that readers with dyslexia take longer to engage and disengage attention resulting in a prolonged time in which it takes to process information (Hari, & Kiesilä, 1996; Helenius et al., 1999; Merzenich et al., 1993). Specifically, the SAS Hypothesis considers deficits in attention to fall specifically within serial attention allocation, whereby serial identification of letters is more challenging for those with dyslexia than for typical readers. Such delay in letter identification would slow down early lexical activation preventing saccades being programmed to target the next word. As discussed in Chapter 1, it has been proposed that SAS may even explain phonological difficulties for readers with dyslexia (Blomert, 2011; Hari & Renvall, 2001), however, research to support such suggestion is still in its infancy.

The final explanation provided for why dyslexic readers make additional fixations compared to non-dyslexic readers relates to saccadic targeting and landing positions. Previous research into skilled reading has demonstrated that readers are more likely to refixate a word when their initial landing position was not in the optimal location (Joseph et al., 2009; McConkie et al., 1991; Vitu et al., 2001). If the fixation location is far from the center of the word, word identification is more difficult (Brysbaert, Vitu, & Schroyens, 1996; O'Regan, 1990). The reader will, therefore, typically make a subsequent fixation in order to gain adequate visual information. In fact, it has been found that dyslexic readers make earlier landing positions into a word compared to their chronologically age matched peers (De Luca et al., 2002; Hawelka et al., 2010; MacKeben et al., 2004; Pan et al., 2014). Thus, dyslexic readers may make additional fixations due to their earlier landing positions. In fact, this suggestion is supported by both Experiment 1 and Experiment 2 reported within this thesis. Specifically, Experiment 1 demonstrated that dyslexic adult readers land earlier in a word compared to skilled adult readers. Furthermore, Experiment 2 provided additional numerical support for this suggestion by demonstrating a similar trend for children with dyslexia compared to typically developing children matched on chronological age and typically developing children matched on reading age.

Although it is unclear exactly why dyslexic readers land earlier within a word, these early landing positions may indicate that dyslexic readers are less able to correctly target their saccades to the preferred viewing location due to magnocellular dysfunction (Boden & Giaschi, 2007). It must be noted, however, it is generally accepted that the differential eye movement patterns demonstrated by readers with dyslexia are not the cause of dyslexia (Rayner, 1985b). Another explanation for early landing positions may be due to a lack of parafoveal information, as this information is used to target saccades (Schotter et al., 2012). The suggestion that dyslexic readers lack parafoveal information seems somewhat counterintuitive to the results presented within this thesis as the first two experiments demonstrate that dyslexic readers encode parafoveal information from the initial 2 letters of the parafoveal word, and the final experiment of the thesis demonstrates that dyslexic adults extract information further into the middle of the parafoveal word. The current research, however, did not determine whether dyslexic readers can allocate their attention far enough into the parafovea in order to gain sufficient information to target saccades correctly (e.g. information about word length or spaces between words). In fact, dyslexic readers have been found to have a reduced perceptual span compared to non-dyslexic readers (Rayner et al., 1989), thus is it possible that they do receive reduced parafoveal information which impacts their saccade targeting and landing positions.

While there is a lack of evidence to determine the exact causality of dyslexic differences in foveal eye movement behaviour compared to non-dyslexic readers, the results reported within this thesis, (such as increased within word fixation counts and early landing positions) are indicative of serial sublexical grapheme–phoneme conversion in order to access phonology and meaning. Thus this research further supports the work Hawelka et al. (2010) who found similar results for dyslexic adult readers and provides additional support for both attentional (Bosse et al., 2007) and phonological theories of dyslexia (Snowling, 2000).

6.2.2 Parafoveal processing

In addition to exploring the eye movement patterns of adults and children with dyslexia, the current thesis aimed to examine parafoveal processing during reading for these readers. Recall, one of the key issues identified in Chapter 1 was the lack of research exploring parafoveal processing during reading for those with dyslexia. As such, the three experiments detailed in this thesis aimed to further our understanding of parafoveal processing for both dyslexic adults and children, by exploring whether dyslexic readers could gain parafoveal preview benefits during reading.

Do dyslexic readers show parafoveal preview benefits during reading?

Using the boundary paradigm (Rayner, 1975) to manipulate parafoveal information, all three experiments reported in this thesis demonstrated that dyslexic readers were able to allocate their attention to the parafoveal word in order to gain parafoveal preview benefits during silent sentence reading. Specifically, Experiment 2 demonstrated that children with dyslexia were able to gain parafoveal preview benefit during silent sentence reading and both Experiment 1 and Experiment 3 demonstrated that dyslexic adults also gain parafoveal preview benefit during silent sentence reading. Thus, similarly to non-dyslexic children and adults (Pagán et al., 2016; Schotter et al., 2012; Tiffin-Richards & Schroeder, 2015), dyslexic readers were able to allocate their attention to the parafovea in order to pre-process information from the parafoveal word and facilitate the encoding of the word once it was later fixated.

Within Experiment 2, children with dyslexia and both non-dyslexic child groups (typically developing children matched on chronological age and typically developing children matched on reading age) demonstrated the ability to allocate their attention to the parafoveal word and gain parafoveal preview benefits during silent sentence reading. For the dyslexic children and typically developing children matched for reading age, parafoveal preview benefits occurred in later measures of reading in comparison to the typically developing children matched on chronological age. Both of these less skilled reading groups had the attentional resources to allocate their attention to parafoveal processing, but their encoding of the pre-processed information was slower than that of a more skilled reader. Indeed, dyslexic children and reading age matched typically developing children were less efficient at activating the correct lexical candidate and, as such, were less likely to gain parafoveal preview benefit during early measures of reading. Such findings are consistent with the idea of a developmental increase in the rate of lexical processing (Reichle, Liversedge, Drieghe, et al., 2013). These findings, therefore, indicate that efficient parafoveal processing develops alongside reading skill; as reading skill increases, lexical processing becomes more efficient and demands less attentional resources, thus allowing attentional resources to be allocated to parafoveal processing and parafoveal preview benefits to help to quickly activate the correct lexical candidate.

In contrast to the dyslexic children, dyslexic adult readers did not show the same delay in the timeframe in which they showed parafoveal preview benefits; dyslexic adults were able to gain preview benefit during early measures of single fixation duration and first fixation duration. Indeed, by the time dyslexic readers reach adulthood, their reading skill is of an adequate level to allow parafoveal preview benefits to occur within early measures of reading. This provides further support that delayed parafoveal preview benefits (parafoveal preview benefits that occur in later eye movement measures) and slower lexical activation are part of typical reading development for dyslexic and non-dyslexic readers.

The finding that dyslexic adults and children can gain parafoveal preview benefit during reading supports and extends the body of work demonstrating parafoveal preview benefit in skilled adult readers (see Rayner, 1998, and Schotter et al., 2012 for reviews) and typically developing child readers (Häikiö et al., 2010; Marx et al., 2015; Pagán et al., 2016; Tiffin-Richards & Schroeder, 2015). Furthermore, the results reported in this thesis also support research demonstrating that dyslexic readers can parafoveally process information specifically during RAN (a task which requires readers to allocate their attention to an array of individual letters or numbers in order to name them as quickly and accurately as possible; Jones et al., 2008, 2010, 2013; Yan et al., 2013), and extends this work to reveal dyslexic parafoveal processing during the more cognitively demanding task of silent sentence reading. It is important to note, however, that the results of the current thesis differ to those found by Chace et al. (2005) who used the boundary paradigm to explore parafoveal processing during reading for a group of skilled and less skilled adult readers.

Whilst Chace et al. (2005) did not directly test dyslexic readers; they found no evidence of parafoveal processing in their group of less skilled readers (as measured by the Nelson Denny tests of vocabulary and reading comprehension). As discussed in detail in throughout the thesis, the contrast in results from Chace et al. (2005) compared to those of the current thesis may be explained upon two accounts;

1) their less and more skilled adult readers were selected using the Nelson Denny test which measures a readers ability to extract meaning from language rather than phonological decoding, thus their sample of less skilled adult readers may not reflect dyslexic parafoveal processing abilities but that of poor comprehenders, and 2) due to increased foveal load (caused by low frequency pre-target words) preventing the readers from having enough attentional resources to allocate their attention to the parafovea for pre-processing. Indeed, there is a body of work which demonstrates that if the fixated word is difficult to process, readers obtain less preview benefit from the parafoveal word (Henderson & Ferreira, 1990; Kennison & Clifton, 1995; White et al., 2005a; Balota et al., 1985; Drieghe et al., 2005; Vignali, Hawelka, Hutzler, & Richlan, 2019).

Whilst Experiment 1 & 2 of this thesis were specifically designed to ensure dyslexic readers had enough attentional resources to encode parafoveal information (e.g. reduced foveal load through the use of high frequency 5-6 letter pre-target words, and ensuring the parafoveal manipulation occurred only within the initial letters of the parafoveal word), the third Experiment used the stimuli from Chace et al. (2005), which included pre-target words of varied length and frequency scores, as well as parafoveal manipulations that occurred in the beginning and middle of the parafoveal word. Even when using the stimuli from Chace et al. (2005), the results indicated that dyslexic readers did gain parafoveal preview benefit during silent sentence reading. Thus, dyslexic readers do have the attentional resources and ability to parafoveally process information during reading and can gain preview benefit from both the initial letters and middle letters of the parafoveal word. In contrast, however, readers who have difficulty with reading comprehension show difficulty in allocating their attention to the parafovea or in having enough attentional resources for parafoveal processing (Chace et al., 2005).

Contrary to the proposal that readers with dyslexia have difficulty in allocating their attention to the next word due to deficient posterior parietal lobe functioning (Boden & Giaschi, 2007), the studies in this thesis indicate that dyslexic readers do not have a deficit in their ability to shift their attention from the foveal to parafoveal word during silent sentence reading. Indeed, one of the possible manifestations of magnocellular dysfunction during reading is that dyslexic readers have difficulty in allocating their attention the next word (Boden & Giaschi, 2007; Stein & Walsh, 1997; Steinman, Steinman, & Garzia, 1996, 1998; Vidyasagar, 1999). Although there is evidence indicating that the posterior parietal cortex is key to aspects of visual spatial attention (for a review see Boden & Giaschi, 2007), there is little research to demonstrate dyslexic difficulties in attention orienting specifically during reading. There has been research which examines attention orienting and visual search for dyslexic readers (Buchholz & Davies, 2005; Buchholz & McKone, 2004 ; Casco & Prunetti, 1996; Facoetti, Paganoni, & Lorusso, 2000; Facoetti et al., 2000; Sobotka & May, 1977), but there is a paucity of research actually examining attention allocation from the currently fixated word to the next word for dyslexic readers during reading. All three experiments of this thesis, however, specifically examined this by exploring whether dyslexic readers could allocate their attention to the parafoveal word in order to gain parafoveal preview benefits during reading. In fact, all three experiments provided evidence that dyslexic readers can allocate their attention to the parafoveal word in order to gain preview benefits; there was no evidence to suggest that dyslexic readers demonstrate difficulty in allocating their attention the upcoming word. Thus, the ability to allocate attention from the foveal word to the parafoveal word is not a causal factor in the reading difficulties for the dyslexic readers reported in these experiments.

It is important to note, however, that whilst the current sample of dyslexic readers do not have a deficit in allocating their attention from one word to the next, they may still have difficulty in effectively allocating their attention between individual letters within a word. Recall, the SAS Hypothesis (Hari & Renvall, 2001; Lallier et al., 2010) suggests that dyslexic readers have deficits in attention whereby serial identification of letters is more challenging for those with dyslexia than for typical readers. It is, therefore, possible for readers with dyslexia to demonstrate attention allocation deficits within words even though they are able to allocate their attention from one word to another in order to benefit from parafoveal processing. Attention allocation to individual letters will be discussed in more detail in the following section, which focuses on the type of information that is encoded from the parafovea. Specifically, Experiment 1 & 2 explored orthographic parafoveal processing of letter identity and letter position, and Experiment 3 explored parafoveal processing of phonological information. The findings from Experiment 1 & 2 on orthographic parafoveal processing will be discussed first.

Do readers with dyslexia encode orthographic information from the parafovea?

Orthographic parafoveal processing capabilities were examined in both children with dyslexia (Experiment 2) and adults with dyslexia (Experiment 1) in order to assess whether readers with dyslexia were able to effectively allocate their attention to individual letters within the parafoveal word to encode letter identity and letter position information. Recall, it has been proposed that attention deficits may impact a dyslexic reader's ability to accurately encode letter position information during reading (Boden & Giaschi, 2007; Cornelissen, Hanson, Hutton, et al., 1998; Hari & Renvall, 2001; Vidyasagar & Pammer, 2010; Whitney & Cornelissen, 2005) and, in extreme cases, readers with dyslexia may use an *object style* recognition method in which each word is encoded as a whole visual object rather than using a serial left to right encoding mechanism to encode letter position information (Whitney & Cornelissen, 2005).

Specifically, in order to examine how orthographic information is encoded parafoveally, Experiment 1 and Experiment 2 explored two key preview effects; the viewing durations on identical previews compared transposed-letter previews, and, also the TL effect which is the comparison of viewing durations for transposed-letter previews to substituted-letter previews. A preview benefit for identical previews compared to transposed-letter previews indicates that readers are encoding letter position information from the parafovea. A preview benefit for transposed-letter previews compared to substituted-letter previews indicates that readers are able to encode letter position information flexibly; letter position and identity information are encoded independently so that readers can gain benefit from having the correct letter identity in the incorrect letter position. The following section will discuss each of these effects in more detail.

Firstly, contrary to suggestions that attention deficits may impact a dyslexic readers ability to accurately encode letter position information during reading (Boden & Giaschi, 2007; Cornelissen, Hanson, Hutton, et al., 1998; Hari & Renvall, 2001; Vidyasagar & Pammer, 2010; Whitney & Cornelissen, 2005), Experiment 1 and 2 showed that dyslexic adults and children were able to encode letter position from the parafovea during silent sentence reading. Both adults and children with dyslexia showed a greater preview benefit for identical parafoveal previews compared to transposed-letter parafoveal previews, thus indicating that they were able to allocate their attention to the parafoveal word and encode letter position information. Although dyslexic readers were able to encode letter position during parafoveal processing, dyslexic adults showed a greater preview benefit for identical previews compared to transposed-letter previews than the skilled adult readers. Thus, dyslexic adult readers had a greater reliance on parafoveal letter position for lexical identification compared to skilled reading adults. Such finding is contrary to the proposal of Whitney and Cornelissen (2005) who suggested that dyslexic readers have attentional deficits that disrupt the correct mapping of graphemes to phonemes, resulting in a reduced requirement for encoding the correct left-to-right position of individual letters within a word.

In fact, a similar trend occurred for both dyslexic children and typically developing children matched for reading age compared to the typically developing children matched for chronological age; dyslexic readers and reading age matched controls were more reliant on letter position for lexical identification compared to the typically developing children matched on chronological age. The finding that dyslexic children and typically developing children matched on reading age show similar dependence on letter position information suggests that reading ability modulates parafoveal processing of letter position information in developing readers. It is important to note, however, that dyslexic adults still showed a greater dependence on letter position information during parafoveal processing compared to skilled adult readers. Therefore, although dyslexic children and typically developing children matched on reading age show similar dependence on letter position during parafoveal processing, as their reading skills improve, the typically developing children become less dependent on letter position information for lexical activation. In contrast, dyslexic children continue to show increased dependency on letter position during parafoveal processing as they progress into adulthood. Whilst it may initially appear that increased dependence on letter position is explained by reduced reading skills, and therefore occurs as a function of a dyslexic reading delay, such effect still occurs for dyslexic adults and consequently cannot purely be a developmental lag. Increased dependence on letter position may initially occur due to delay in reading development, but the difference persists throughout dyslexic reading. The potential causes for this increased dependence on letter position information will be discussed in further detail later in this section.

Another difference in dyslexic reader's ability to encode letter position information during parafoveal processing compared to non-dyslexic readers was in which eye movement measures the preview benefit occurred; dyslexic children encoded letter position during later eye movement measures compared to typically developing children matched on chronological age. Specifically, both dyslexic children and typically developing children matched for reading age only demonstrated significant preview benefits for identical previews compared to transposed-letter previews during later measures of reading such as gaze duration, go-past time and total reading time, whereas chronological age matched typically developing children encoded letter position during both single fixation duration and first fixation duration. This indicates that letter position information was encoded at a slower rate for both dyslexic readers and typically developing children matched on reading age compared to the typically developing children who were matched to the dyslexic readers on chronological age. This pattern of results, however, did not occur for adult dyslexic readers who were able to encode letter position during early measures of single fixation duration and first fixation duration. Thus, by the time dyslexic readers reach adulthood, they still have a greater reliance on letter position for lexical activation but are no longer slower to demonstrate parafoveal preview benefit from encoding letter position.

In fact, the delay in letter position encoding, demonstrated by dyslexic children and reading age matched children compared to typically developing children matched for chronological age, indicates that less skilled readers are not as efficient in using letter position information to facilitate lexical activation during parafoveal processing. This is supported by research demonstrating that precise letter position encoding develops slower than precise letter identity encoding (Castles et al., 2007). Taken together with the fact that dyslexic adult readers no longer show this delay in letter position encoding, the finding that dyslexic children demonstrate letter position encoding in later measures of eye movement behaviour is, therefore, indicative of typical reading development and not a dyslexic specific deficit.

Further to demonstrating that dyslexic readers encode letter position information during parafoveal processing, Experiment 1 and Experiment 2 examined whether dyslexic readers showed a TL effect. The TL effect occurs when readers are able to gain benefit from encoding the correct letter identity of letters that are in the incorrect letter position; thus, indicating that readers are encoding letter identity and letter position information independently using a flexible letter position encoding mechanism (such as; the SOLAR model Davis, 1999, 2010; the Open Bigram model, Grainger & van Heuven, 2003; Grainger, Granier, Fariolli, van Assche & van Heuven, 2006; Grainger & Ziegler, 2011; the Overlap model, Gómez et al., 2008; the SERIOL model, Whitney, 2001). In support of previous research (Johnson et al., 2007; Pagán et al., 2015; Tiffin-Richards & Schroeder, 2015), Experiment 1 and 2 found that skilled adult readers and typically developing child readers demonstrated the TL effect in which they showed greater preview benefit for words with transposed letters compared to words with substituted letters. This provides further evidence that non-dyslexic readers use a flexible letter position encoding mechanism; they independently encode letter identity and letter position during parafoveal processing. Furthermore, Experiment 1 and Experiment 2 demonstrated that dyslexic children and adults also showed a TL effect; dyslexic readers were able to encode letter identity independently to letter position information during parafoveal processing. Such result indicates that, similar to non-dyslexic readers, dyslexic readers use a flexible letter position encoding mechanism. This is contrary to Whitney and Cornelissen's suggestion that dyslexic readers may use an object style of word recognition due to an underdeveloped attentional location gradient that does not allow for letter position encoding (Whitney & Cornelissen, 2005).

It must be noted, however, that although dyslexic readers demonstrated a TL effect, there were differences in the TL effect for dyslexic readers compared to their non-dyslexic peers. Similarly to the results for identical previews compared to transposed-letter previews (in which a preview benefit for identical previews indicates that letter position encoding occurs), both dyslexic children and typically developing children matched on reading age, demonstrated the TL effect during later eye movement measures (such as gaze duration, go-past time and total reading time) compared to typically developing children matched on chronological age who showed the effect in early measures (such as single fixation duration and first fixations duration). This is not surprising given that dyslexic children and reading age matched controls only show evidence of letter position encoding in later measures of eye movement behaviour. Dyslexic adults also showed a delayed TL effect compared to non-dyslexic adults. This result, however, is somewhat surprising because dyslexic adults were able to encode letter position information during early eye movement measures; they demonstrated preview benefits for identical previews compared to transposed letter previews during single fixation duration and first fixation. Thus, although dyslexic adults can encode letter position in early measures of reading, they have difficulties in flexibly encoding letter position which results in a delay in their ability to flexibly encode letter position. This difficulty in flexible letter position encoding, therefore, is a persistent and specific deficit in dyslexic reading that occurs in both childhood and adulthood. In contrast, for typically developing children, delayed TL effects appear to occur as part of typical reading development and as their reading skills improve, readers are able to independently encode letter position during their initial fixations.

In sum, the results of Experiment 1 and Experiment 2 demonstrated a number of differences in dyslexic orthographic parafoveal processing, which occur independently of reading skill and impact dyslexic readers as children and adults. Specifically, dyslexic readers consistently showed increased dependence on letter position information for lexical activation and only demonstrated independent encoding of letter position and letter identity during late measures of reading. Whilst increased dependence on letter position information is normal for young readers (Ehri, 2005; 2010), it is less clear as to why dyslexic readers have a specific dependence on letter position information that occurs independently of typical reading development and persists throughout their lifespan.

One explanation as to why dyslexic readers have a specific dependence on letter position information is that they have limitations in their ability to encode letters in parallel (a reduced VA span Bosse et al., 2007; Prado et al., 2007; Valdois et al., 2004) which causes them to adopt a serial sublexical method for reading. As discussed earlier in this chapter, a VA span deficit would result in dyslexic readers encoding smaller chunks of information and, therefore, having to make more fixations to ensure they encode each word. This requirement for additional fixations would then result in a greater reliance on letter position to accurately map these chunks of information together to form a full orthographic representation of the word.

The second explanation for increased dependence on letter position information is that, in line with the Phonological Deficit Hypothesis (Liberman, 1973; Snowling, 1995; Snowling, 2000; Stanovich, 1988), dyslexic readers have difficulties in accurately mapping phonological and orthographic information and, therefore do not develop the high-quality lexical representations required for skilled adult reading (Perfetti, 2007). Indeed, because of their difficulties in mapping phonology to orthography, dyslexic readers are slower to access phonology from orthographic representations (Bergmann & Wimmer, 2008) and are less likely to form high-quality orthographic representations of words (Hulme & Snowling, 2013; Lervåg & Hulme, 2009). Because of their underspecified lexical representations, dyslexic readers then rely on the fine-grained route for orthographic encoding (Grainger & Ziegler, 2011). The fine-grained route requires chunking visual input into frequently co-occurring contiguous letter combinations, such as multiletter graphemes (e.g., sh, th, and ph) and morphemes (e.g., ing, er, and re) in order to access semantics; therefore, the fine grain route depends on the precise ordering of letter position information. As such, readers with dyslexia would have greater dependence on letter position encoding for lexical activation. This is consistent with research demonstrating that flexible letter position encoding occurs when lexical representations are encoded more precisely in children (e.g., Grainger & Ziegler, 2011; Grainger et al., 2012; Lété & Fayol, 2013; Ziegler et al., 2014)

Both of these suggestions are in line with the proposal that dyslexic readers rely upon serial sublexical grapheme–phoneme conversion in order to access phonology and meaning (Hawelka et al., 2010) and provide additional support for the foveal eye movement data reported in this thesis.

Lastly, the explanations as to why dyslexic readers show delayed TL effects are closely aligned with the explanations of why dyslexic readers have increased dependence on letter position. Indeed, if readers with dyslexia rely more heavily upon correct letter position for lexical identification, flexible encoding of letter position and letter identity may not be as particularly important to their reading. Therefore, whilst dyslexic readers do use a flexible letter position encoding mechanism, they are less efficient at processing correct letter identity information when it is in the incorrect letter position, causing the TL effects to occur within later eye movement measures. Furthermore, as dyslexic readers often require multiple fixations to achieve word identification, one would predict that the TL effect would occur at delayed timeframe and, therefore, occur in late eye movement measures which take into account multiple fixations. Dyslexic readers' delayed TL effects can, therefore, also be explained by their reliance upon serial sublexical grapheme–

phoneme conversion in order to access phonology and meaning (Hawelka et al., 2010)

It is, however, important to note that the greater dependence on correct letter position information, found for dyslexic readers compared to non-dyslexic readers, might be a finding limited to these initial letters. Recall, as explained in Chapter 3, the initial letters were selected for the TL manipulation due to their close proximity to the foveal word, but, also due to the intrinsic importance of the initial letters for lexical identification (White et al., 2008). In fact, skilled readers encode the initial letters of a word less flexibly than internal letters (Johnson & Dunne, 2012; Johnson & Eisler, 2012; Johnson et al., 2007; Tiffin-Richards & Schroeder, 2015; White et al., 2008) and this may be explained by the fact that words need to be sequentially processed from left-to-right in order to correctly activate phonological representations and establish the phonological onset of the word. The initial letters may, therefore, be encoded less flexibly to allow for correct sequential phonological encoding, which can then help to restrict the number of suitable lexical candidates (Folk & Morris, 1995), or aid in activating the correct lexical representation (Lima & Inhoff, 1985). Dyslexic readers, however, have difficulties in phonological processing (Snowling, 2000). As such, their less flexible letter position encoding may be specific to these initial letters because they need to ensure accurate phonological encoding in order to help efficiently identify the word; their difficulties in phonological processing cause a greater reliance upon the correct initial letter position information to help improve lexical identification.

It is, therefore, possible that a dyslexic readers' reduced flexibility in letter position encoding is due to a heightened importance for these initial letters, caused by their difficulty in encoding and representing phonological information (Snowling, 2000). Thus dyslexic readers may show a specific difficulty in the flexible encoding of initial letter position, because of the sequential nature of encoding phonological information from left to right, rather than because they have an attentional deficit related to the amount of information they can encode in parallel (Bosse et al., 2007; Prado et al., 2007; Valdois et al., 2004).

Do readers with dyslexia encode phonological information from the parafovea?

Whilst the first two experimental chapters of this thesis focused upon whether dyslexic readers could encode orthographic information from the parafovea, the final experiment (Experiment 3) explored whether dyslexic adults could encode phonological information from the parafovea. Dyslexic readers have difficulty in extracting phonological information from orthographic form (Liberman, 1973; Snowling, 1995; Snowling, 2000; Snowling & Hulme, 2012; Stanovich, 1988); therefore, whilst they do access orthographic information parafoveally, they may not gain any benefit for parafoveal phonological information. It was, therefore, predicted that dyslexic readers would show difficulties in phonological parafoveal processing compared to non-dyslexic readers. In order to test this, Experiment 3 used the boundary paradigm to compare the following parafoveal preview manipulations: 1) identical previews, 2) homophone previews, 3) orthographic control previews, and 4) a random string of consonants. Specifically, by exploring the benefit of the homophone previews compared to the orthographic control previews, it is possible to determine whether phonological information is encoded in addition to orthographic information. In fact, this design has been previously used to identify phonological preview benefits in skilled adult readers (Chace et al., 2005; Pollatsek et al., 1992).

Although the experimental design was replicated from Chace et al. (2005), the results of Experiment 3 indicated that neither skilled adult readers nor dyslexic adult readers showed a benefit of phonological information compared to orthographic information. Whilst such result is consistent with a body of work demonstrating that phonological preview benefits are notoriously difficult to identify (Choi & Gordon, 2014; Lee et al., 1999; Rayner et al., 1980), such a finding was unexpected given that the same experimental stimuli had previously been used to identify phonological preview benefits during skilled adult reading (Chace et al., 2005). However, as discussed in Chapter 5, one possible explanation for the lack of evidence supporting phonological parafoveal preview benefits in skilled adult reading may be due to differences in the native language of the samples selected for the study. Indeed, Chace et al. (2005) conducted their research with native American English readers whereas Experiment 3 was conducted with native British English readers. Within the study reported by Chace et al. (2005), the word frequency of the target words were matched across three of the preview conditions (identical previews, homophone previews, orthographic control previews) using word frequency scores from the Francis and Kučera (1982) database. Whilst the Francis and Kučera (1982) word frequency scores were previously regularly used in samples of British English readers (e.g. Ashby et al., 2005; Kirkby et al., 2013; White et al., 2005a; 2005b), this database is now often considered to be somewhat out-of-date (Balota et al., 2004; Brysbaert & New, 2009; Burgess & Livesay, 1998; Zevin & Seidenberg, 2002). For British readers, the BNC (British National Corpus) is now more frequently used. Indeed, when using the BNC to measure word frequency for the target words in the Chace et al. (2005) stimuli, there was greater variation in the word frequency scores compared to that found when using the Francis and Kučera (1982) database. As such, the variations in word frequency scores may have impacted the ability to find phonological preview benefits for skilled and dyslexic readers.

Due to the lack of significant results across both reading groups, it is impossible to draw conclusions on dyslexic readers' ability to phonologically process parafoveal information during silent sentence reading. Further research is required in order to address this research question and determine whether dyslexic readers show differences in phonological preview benefits compared to non-dyslexic readers. Future research exploring phonological parafoveal processing with British readers should use the BNC to determine and control for word frequency as the word frequency scores from the Francis and Kučera (1982) database may have enough variation to mask the small effects of phonological parafoveal processing.

6.2.3 Overall discussion

The research presented within this thesis provides a detailed account of foveal and parafoveal processing for adults and children with dyslexia in order to develop our understanding of dyslexic eye movement behaviour and further inform theories of dyslexia. The current findings demonstrated that dyslexic readers show consistent and dyslexic-specific reading difficulties in both foveal and parafoveal processing during silent sentence reading compared to non-dyslexic readers. Specifically, during foveal processing, dyslexic readers required additional fixations, which resulted in longer fixation durations such as gaze durations and total reading times. In addition to showing increased fixations, dyslexic readers also showed evidence of earlier landing positions compared to non-dyslexic readings. In measures of parafoveal processing, dyslexic readers showed orthographic parafoveal preview benefit, however, they also demonstrated a greater reliance on letter position information for lexical activation, which in turn impacted their ability to flexibly encode letter position. Taken together, these results indicate that dyslexic readers rely upon serial sublexical grapheme-phoneme conversion for word processing (Hawelka et al., 2010) and that is caused by a dyslexic specific deficit and not explained by their reduced reading skill.

When using a sublexical route for reading, readers have to make more fixations in order to encode the full word. Sublexical processing requires that small chunks of information are serially encoded for grapheme-phoneme conversion in order to eventually gain a full orthographic and phonological representation of the word and access word meaning. In fact, a reliance on the serial sublexical method implies that dyslexic readers have an orthographic lexicon deficit in which they are unable to find a match within the orthographic lexicon and therefore cannot activate word phonology and meaning through this efficient orthographic route to word recognition. This would prevent dyslexic readers from learning to target their saccades towards the centre of the word, as they are unable to encode the whole word within one fixation. Instead, they need to encode information serially and consequently make earlier landing positions compared to non-dyslexic readers, with the expectation that their additional fixations on that word would allow for the rest of the letters to be encoded. Due to the serial nature of sublexical processing and decoding, readers need to ensure they are encoding the letter information in the correct order to achieve correct lexical activation. Thus, letter position information is more important when relying upon a serial sublexical route for word recognition as readers make multiple fixations and letter order needs to be retained for grapheme-phoneme conversion to take place.

These findings are consistent with both phonological and attention deficit theories of dyslexia. Indeed, the Phonological Deficit Hypothesis (Liberman, 1973; Snowling, 1995; Snowling, 2000; Stanovich, 1988) suggests that readers with dyslexia have difficulties with phonological awareness, which then impacts their ability to store high-quality orthographic representations of words (Hulme & Snowling, 2013; Lervåg & Hulme, 2009) and prevents quick access from orthographic to phonological word representations (Bergmann & Wimmer, 2008). Dyslexic readers, therefore, use a serial sublexical method of reading, which relies upon the slow and effortful phonological decoding of graphemes to phonemes and requires accurate mapping of letter position. In addition to the Phonological Deficit

Hypothesis, the results from this thesis are also consistent with attention deficits theories of dyslexia. Specifically, although dyslexic readers did not show an attention deficit in their ability to allocate their attention to the parafovea during reading, a VA span deficit (Bosse et al., 2007; Valdois et al., 2004) could explain their reliance on a serial sublexical method for reading. The VA span suggests that readers with dyslexia have a reduced area in which they can allocate attention, which, in turn, limits the number of letters that can be processed in parallel. As such, readers with dyslexia can only encode a small amount of information in parallel. This means that they would need to make additional fixations to extract the rest of the letters from the word, leading to a serial sublexical method to reading. Whilst the current results cannot draw clear distinctions between the competing theories, they do indicate that the serial sublexical grapheme–phoneme conversion method of reading adopted by dyslexic adults and children is representative of more than just a reading delay caused by dyslexic readers' poor reading skills and is, in fact, representative of a specific dyslexic reading difficulty.

6.3 Challenges in the current research

One of the greatest challenges within the current body of research was that of obtaining enough power in order to establish significant effects and interactions. Whilst many of the results did reach significance, there were still some findings that were perhaps underpowered. There were two main contributing factors to this challenge: the participant sample and the nature of preview benefits.

Collecting data with children and special populations such as dyslexic readers is typically challenging for a number of reasons. Firstly, recruitment of children and special populations takes time as it can be more challenging to find these individuals compared to a typical university student sample. Therefore, it is not unusual to have relatively small sample sizes for studies of children or dyslexic readers and this occurs even more so for studies of eye movement behaviour (e.g. Blythe et al., 2006; 2009; 2010; Joseph et al., 2009). Indeed, as highlighted by Blythe and Joseph (2011) collecting eye movement data can be challenging as recording accurate eye movement data requires that participants sit very still, often for prolonged periods of time; this can be particularly difficult for children and special populations. In fact, collecting accurate eye movement data is particularly important when using the boundary paradigm (Rayner, 1975) as the parafoveal preview manipulation relies upon a gaze contingent change. Thus, if the calibration of the eye tracking equipment is not accurate, then the boundary will trigger at the incorrect time point and the participant may not get the intended parafoveal preview. Therefore, not only were calibrations accuracies checked, but also a strict exclusion criterion was followed to make sure that the data was as accurate as possible. This led to a relatively large amount of data loss, which is not unusual for boundary paradigm studies (Chace et al., 2005; Johnson et al., 2007), but does reduce the amount of data gathered from each participant. As such, due to the challenging nature of recruitment and the need for extremely accurate recordings, it was difficult to collect a lot of data and obtain enough power.

Another challenge with collecting and analysing data from children and special populations is that of the increased variance within the samples. Within the current thesis data was collected from a wide range of children, varying in both their chronological ages as well as their reading skill, both of which can impact their eye movement behaviour. Furthermore, dyslexia is a widely heterogeneous neurodevelopmental disorder in which case there is often great variance between readers with dyslexia (Hynd & Cohen, 1983). Whilst increased variance is typical for such groups, it can become a particular challenge when collecting eye movement data to explore parafoveal preview benefits. Specifically, parafoveal preview benefits are very small in duration; a typical TL effect for a skilled adult reader is approximately between 10-20 ms for a manipulation that occurs within the internal letters of a word (Johnson et al., 2007). Thus, when introducing small samples sizes (due to difficulties in recruitment) and variation in eye movement behaviour (due to the nature of the sample), it becomes even more challenging to ensure that the experimental design for parafoveal preview manipulations have enough power to establish statistically significant results should they exist.

An additional challenge relating to the experimental design of both Experiment 1 and Experiment 2 was deciding where within the parafoveal word the orthographic parafoveal preview manipulation should occur. Recall, this thesis provides initial exploration of dyslexic parafoveal processing during reading, As such, it was initially unclear as to whether readers with dyslexia would in fact show parafoveal preview benefits during reading. Therefore, for the initial experiments of this thesis, reading conditions were specifically manipulated to be favourable in order to increase the likelihood of finding parafoveal preview benefits for readers with dyslexia. Indeed, as dyslexic readers have been found to have a reduced perceptual span (Rayner et al., 1989) and/or VA span (Bosse et al., 2007; Prado et al., 2007; Valdois et al., 2004), it was important to include the parafoveal manipulation early within the parafoveal word. Based on this, and the proposal that the initial letters may have an additional intrinsic importance related to phonological processing, it was decided that the orthographic parafoveal preview manipulations should occur within the initial two letters of the parafoveal word. As mentioned above, the typical TL effect is very small in magnitude, even for internal letters of a word. TL effects are, however, reduced for initial letters of the word (Johnson et al., 2007). Thus, whilst the orthographic preview manipulations were placed within the initial letters of the word to ensure readers with dyslexia were able to demonstrate parafoveal preview benefits, if they were indeed able to, this also made it perhaps more challenging to find TL effects for both dyslexic and non-dyslexic readers.

The research presented within this thesis is, to my knowledge, the first body of work to explore parafoveal preview benefits during reading for dyslexic adults and children. The paucity of research into dyslexic parafoveal processing during reading may somewhat be explained by the challenges listed above. This thesis, however, aimed to further understand parafoveal processing during dyslexic reading; as such, decisions were made to try and address the challenges that come with exploring parafoveal preview benefits for special populations. First, whilst it was difficult to recruit dyslexic children as part of the research, it was slightly less challenging to recruit typically developing children. Therefore, it was decided that the groups of typically developing children need not be restricted to the sample size of the dyslexic group, thus allowing for more data to be collected for typically developing children. A further consideration was that of the method of analysis. Indeed, as the sample sizes were likely to be uneven, with missing data from following a strict exclusion criterion, linear mixed models were selected to analyse the data. As discussed in detail in Chapter 2, LMMs can accommodate for instances of missing data and uneven sample sizes, thus making the analysis more robust given the challenges relating to sample and preview effects. Even though there were challenges related to conducting this research, there were a range of significant findings into dyslexic parafoveal processing during reading and, as such, this work provides a useful basis for future work that can help us further develop our understanding of dyslexic parafoveal processing during reading.

6.4 Future research

Whilst the current thesis provides insight into foveal and parafoveal processing for children and adults with dyslexia compared to non-dyslexic readers, there is still much more research required to further our understanding of dyslexic reading deficits. Specifically, this research indicates that dyslexic readers rely upon a serial sublexical method of word recognition. The current research, however, was not designed to fully address the issue of causality. Thus further research is required to understand why dyslexic readers rely upon a serial sublexical method of reading. Specifically, dyslexic readers were found to make more fixations compared to non-dyslexic readers. As discussed earlier within this discussion chapter, there are a number of explanations as to why this might be the case and future work should examine these explanations in more detail.

In addition to providing support for a serial sublexical method of reading, the current research provides an initial body of work to further our understanding dyslexic parafoveal processing during reading. However, as these studies are the first to establish parafoveal preview benefits during dyslexic reading, there is still much more research required to further advance our understanding of dyslexic parafoveal processing during reading. Due to the heterogeneous nature of the dyslexic population further research is required to replicate the current findings using other samples of readers with dyslexia. Additional research is also required to determine how far into the parafovea dyslexic readers can allocate their attention and gain parafoveal preview benefit, and to explore whether dyslexic readers show differences in the orthographic parafoveal preview benefits for initial word letters compared to internal and end letters. Furthermore, as the results of the third experiment were inconclusive in regard to whether dyslexic readers can extract phonological information from the parafovea, further research is required to address this question.

Finally, the current thesis aimed to further understand dyslexic eye movement behaviour across development and to better understand the nature of the deficit by including two child controls samples. Additional work is, however, required to fully understand the developmental process and the nature of the deficit for a more readers with dyslexia. Indeed, while the current research helps to address this, there is a lack of longitudinal research examining eye movement behaviour and the nature of the reading deficit for readers with dyslexia. Thus, future research resources should be allocated these areas of research.

References

Acha, J. & Perea, M. (2008). The effect of neighborhood frequency in reading: Evidence with transposed-letter neighbors. *Cognition*, 108, 290-300.

Ackerman, P. T., & Dykman, R. A. (1993). Phonological processes, confrontational naming, and immediate memory in dyslexics. *Journal of Learning Disabilities, 26(9),* 597-609.

Aghababian, V., & Nazir, T. A. (2000). Developing normal reading skills: aspects of the visual processes underlying word recognition. *Journal of experimental child psychology*, *76*(2), 123-150.

Ahissar, M., Protopapas, A., Reid, M., & Merzenich, M. M. (2000). Auditory processing parallels reading abilities in adults. *Proceedings of the National Academy of Sciences*, *97*(12), 6832-6837.

American Psychiatric Association. (2013). *Diagnostic and statistical manual of mental disorders: DSM-5* (5th ed.). Washington, D.C: American Psychiatric Association.

Angele, B., & Rayner, K. (2011). Parafoveal processing of word n+ 2 during reading: Do the preceding words matter?. *Journal of Experimental Psychology: Human Perception and Performance*, *37*(4), 1210.

Angele, B., Slattery, T. J., & Rayner, K. (2016). Two stages of parafoveal processing during reading: Evidence from a display change detection task. *Psychonomic bulletin & review*, *23*, 1241.

Angele, B., Slattery, T. J., Yang, J., Kliegl, R., & Rayner, K. (2008). Parafoveal processing in reading: Manipulating n+ 1 and n+ 2 previews simultaneously. *Visual cognition*, *16*(6), 697-707.

Ashby, J., & Rayner, K. (2004). Representing syllable information during silent reading: Evidence from eye movements. *Language and Cognitive Processes, 19*, 391–426.

Ashby, J., Rayner, K., & Clifton, C. (2005). Eye movements of highly skilled and average readers: Differential effects of frequency and predictability. *The Quarterly Journal of Experimental Psychology Section A*, *58*(6), 1065-1086.

Ashby, J., Treiman, R., Kessler, B., & Rayner, K. (2006). Vowel processing during silent reading: Evidence from eye movements. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 32*, 416–424.

Baayen, R. H., Davidson, D. J., & Bates, D. M. (2008). Mixed-effects modeling with crossed random effects for subjects and items. *Journal of memory and language*, *59*(4), 390-412.

Baizer, J. S., Ungerleider, L. G., & Desimone, R. (1991). Organization of visual inputs to the inferior temporal and posterior parietal cortex in macaques. *Journal of Neuroscience*, *11*(1), 168-190.

Balota, D. A., Cortese, M. J., Sergent-Marshall, S. D., Spieler, D. H., & Yap, M. J. (2004). Visual word recognition of single-syllable words. *Journal of Experimental Psychology: General*, 133, 283-316.

Balota, D. A., Pollatsek, A., & Rayner, K. (1985). The interaction of contextual constraints and parafoveal visual information in reading. *Cognitive Psychology, 17,* 364–390.

Barr, D. J., Levy, R., Scheepers, C., & Tily, H. J. (2013). Random effects structure for confirmatory hypothesis testing: Keep it maximal. *Journal of memory and language*, *68*(3), 255-278.

Bélanger, N. N., Mayberry, R. I., & Rayner, K. (2013). Orthographic and phonological preview benefits: Parafoveal processing in skilled and less-skilled deaf readers. *The Quarterly journal of experimental psychology*, *66*(11), 2237-2252.

Bellocchi, S., Muneaux, M., Bastien-Toniazzo, M., & Ducrot, S. (2013). I can read it in your eyes: What eye movements tell us about visuo-attentional processes in developmental dyslexia. *Research in developmental disabilities*, *34*(1), 452-460.

Bergmann, J., & Wimmer, H. (2008). A dual-route perspective on poor reading in a regular orthography: Evidence from phonological and orthographic lexical decisions. *Cognitive Neuropsychology*, *25*(5), 653-676.

Binder, K. S., Pollatsek, A., & Rayner, K. (1999). Extraction of information to the left of the fixated word in reading. *Journal of Experimental Psychology: Human Perception and Performance, 25,* 1162–1172.

Biscaldi, M., Gezeck, S., & Stuhr, V. (1998). Poor saccadic control correlates with dyslexia. *Neuropsychologia*, *36*(11), 1189-1202.

Blachman, B.A. (2000). Phonological awareness. In M.L. Kamil, P.B. Mosenthal, P.D. Pearson, & R. Barr (Eds.), *Handbook of reading research* (vol. III, pp. 483–502). Mahwah, NJ: Lawrence Erlbaum.

Blanchard, H. E., Pollatsek, A., & Rayner, K. (1989). The acquisition of parafoveal word information in reading. *Perception & Psychophysics, 46,* 85–94.

Blomert, L. (2011). The neural signature of orthographic–phonological binding in successful and failing reading development. *Neuroimage*, *57*(3), 695-703.

Blythe, H. I. (2014). Developmental changes in eye movements and visual information encoding associated with learning to read. *Current Directions in Psychological Science*, *23*(3), 201-207.

Blythe, H. I., Dickins, J. H., Kennedy, C. R., & Liversedge, S. P. (2018). Phonological processing during silent reading in teenagers who are deaf/hard of hearing: an eye movement investigation. *Developmental science*, e12643.

Blythe, H. I., Häikiö, T., Bertam, R., Liversedge, S. P., & Hyönä, J. (2011). Reading disappearing text: Why do children refixate words? *Vision research*, *51*(1), 84-92.

Blythe, H. I., & Joseph, H. S. S. L. (2011). Children's eye movements during reading. In S. P . Liversedge, I. D . Gilchrist, & S. Everling (Eds.), *The Oxford handbook of eye movements* (pp. 643-662). Oxford, UK: Oxford University Press.

Blythe, H., Kirkby, J., & Liversedge, S. (2018). Comments on:"What Is Developmental Dyslexia?" Brain Sci. 2018, 8, 26. The Relationship between Eye Movements and Reading Difficulties. *Brain sciences*, *8*(6), 100.

Blythe, H. I., Liversedge, S. P., Joseph, H. S. S. L., White, S. J., Findlay, J. M., & Rayner, K. (2006). The binocular co-ordination of eye movements during reading in children and adults. *Vision Research, 46,* 3898-3908.

Blythe, H. I., Liversedge, S. P., Joseph, H. S. S. L., White, S. J., & Rayner, K. (2009). The uptake of visual information during fixations in reading in children and adults. *Vision Research, 49,* 1583-1591.

Boden, C., & Giaschi, D. (2007). M-stream deficits and reading-related visual processes in developmental dyslexia. *Psychological bulletin*, *133*(2), 346.

Boets, B., de Beeck, H. P. O., Vandermosten, M., Scott, S. K., Gillebert, C. R., Mantini, D., ... & Ghesquière, P. (2013). Intact but less accessible phonetic representations in adults with dyslexia. *Science*, *342*(6163), 1251-1254.

Boets, B., Vandermosten, M., Poelmans, H., Luts, H., Wouters, J., & Ghesquière, P. (2011). Preschool impairments in auditory processing and speech perception uniquely predict future reading problems. *Research in developmental disabilities*, *32*(2), 560-570.

Borsting, E., Ridder, W. H., Dudeck, K., Kelley, C., Matsui, L., & Motoyama, J. (1996). The presence of a magnocellular defect depends on the type of dyslexia. *Vision Research*, 36, 1047–1053.

Bosse, M. L., Tainturier, M. J., & Valdois, S. (2007). Developmental dyslexia: The visual attention span deficit hypothesis. *Cognition*, *104*(2), 198-230.

Both-De Vries, A. C., De Jong, M. T., Shaul, S., & Bus, A. G. (2016). Parafoveal processing of letters and letter-like forms in prereaders growing up in a left-to-right or a right-to-left writing convention. *Language and Cognition*, *8*(4), 566-586.

Bouma, H. (1970). Visual recognition of isolated lower-case letters. *Vision Research, 11,* 459-474.

Bouma, H. (1973). Visual interference in the parafoveal recognition of initial and final letters of words. *Vision Research, 13(4),* 767–782.

Bouma, H., & Legein, C. P. (1977). Foveal and parafoveal recognition of letters and words by dyslexics and by average readers. *Neuropsychologia*, *15*(1), 69-80.

Bowey, J. (2005). Predicting individual differences in learning to read. In M. J. Snowling & C. Hulme (Eds.), *The science of reading: A handbook* (pp. 155–172). Malden, MA: Blackwell.

Bradley, L., & Bryant, P. E. (1983). Categorizing sounds and learning to read: A causal connection. *Nature, 301,* 419-421.

Bradley, L. & Bryant, P. (1985). *Rhyme and Reason in Reading and Spelling*. Ann Arbor: University of Michigan Press.

Brown, J. I., Bennett, J. M., & Hanna, G. (1981). *The Nelson-Denny Reading Test.* Chicago, IL: Riverside Publishing.

Bruce, D. J. (1964). The analysis of word sounds by young children. *British Journal of Educational Psychology,* 34, 158–170.

Briihl, D., & Inhoff, A. W. (1995). Integrating information across fixations during reading: The use of orthographic bodies and of exterior letters. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 21,* 55–67.

Bryden, M. P. (1961). The role of post-exposural eye movements in tachistoscopic perception. *Canadian Journal of Psychology/Revue canadienne de psychologie*, *15*(4), 220.

Brysbaert, M., Drieghe, D., & Vitu, F. (2005). Word skipping: Implications for theories of eye movement control in reading. In G. Underwood (Ed.), *Cognitive processes in eye guidance* (pp. 53 – 78). Oxford, UK: Oxford University Press.

Brysbaert, M., & New, B. (2009). Moving beyond Kučera and Francis: A critical evaluation of current word frequency norms and the introduction of a new and improved word frequency measure for American English. *Behaviour research methods*, *41*(4), 977-990.

Brysbaert, M., Vitu, F., & Schroyens, W. (1996). The right visual field advantage and the optimal viewing position effect: On the relation between foveal and parafoveal word recognition. *Neuropsychology*, *10*(3), 385.

Buchholz, J., & Davies, A. A. (2005). Adults with dyslexia demonstrate space-based and object-based covert attention deficits: Shifting attention to the periphery and shifting attention between objects in the left visual field. *Brain Cognition, 57,* 30–34.

Buchholz, J., & McKone, E. (2004). Adults with dyslexia show deficits on spatial frequency doubling and visual attention tasks. *Dyslexia*, *10*(1), 24-43.

Burgess, C., & Livesay, K. (1998). The effect of corpus size in predicting reaction time in a basic word recognition task: Moving on from Kučera and Francis. *Behaviour Research Methods, Instruments, & Computers*, *30*(2), 272-277.

Buswell, G . T . (1922). *Fundamental reading habits. A study of their development.* Chicago, IL: University of Chicago Press.

Cabeza, R., & Nyberg, L. (2000). Imaging cognition II: an empirical review of 275 PET and fMRI Studies. *Journal of Cognitive Neuroscience, 12,* 1–47.

Cain, K. (2010). *Reading development and difficulties.* Chichester, England: Wiley-Blackwell.

Cain, K., Oakhill, J., & Bryant, P. (2000). Phonological skills and comprehension failure: A test of the phonological processing deficit hypothesis. *Reading and Writing*, *13*(1-2), 31-56.

Callens, M., Whitney, C., Tops, W., & Brysbaert, M. (2013). No deficiency in left-to-right processing of words in dyslexia but evidence for enhanced visual crowding. *The Quarterly Journal of Experimental Psychology*, *66*(9), 1803-1817.

Casco, C., & Prunetti, E. (1996). Visual search of good and poor readers: effects with targets having single and combined features. *Perceptual and Motor Skills*, *82*(3), 1155-1167.

Castles, A., & Coltheart, M. (1996). Cognitive correlates of developmental surface dyslexia: A single case study. *Cognitive Neuropsychology, 13,* 25–50.

Castles, A., & Coltheart, M. (2004). Is there a causal link from phonological awareness to success in learning to read? *Cognition*, *91*(1), 77-111.

Castles, A., Davis, C., Cavalot, P., & Forster, K. (2007). Tracking the acquisition of orthographic skills in developing readers: Masked priming effects. *Journal of Experimental Child Psychology,* 97, 165–182.

Castles, A., Holmes, V. M., Neath, J., & Kinoshita, S. (2003). How does orthographic knowledge influence performance on phonological awareness tasks?. *The Quarterly Journal of Experimental Psychology*, *56*(3), 445-467.

Catts, H. W., & Adlof, S. (2011). Phonological and other language deficits associated with dyslexia. In S. A. Brady, D. Braze, & C. A. Fowler (Eds.), *Explaining individual differences in reading: Theory and evidence* (pp. 137-151). New York: Psychology Press.

Cestnick, L., & Coltheart, M. (1999). The relationship between language-processing and visual-processing deficit in developmental dyslexia. *Cognition, 71*, 231–255.

Chace, K. H., Rayner, K., & Well, A. D. (2005). Eye movements and phonological parafoveal preview: Effects of reading skill. *Canadian Journal of Experimental Psychology, 59,* 209–217.

Chambers, S. M. (1979). Letter and order information in lexical access. *Journal of Verbal Learning and Verbal Behaviour, 18,* 225–241.

Chen, J., He, Y., Zhu, Z., Zhou, T., Peng, Y., Zhang, X., & Fang, F. (2014). Attention-dependent early cortical suppression contributes to crowding. *The Journal of Neuroscience*, 34(32), 10465–10474.

Chen, N. T., Zheng, M., & Ho, C. S. H. (2018). Examining the visual attention span deficit hypothesis in Chinese developmental dyslexia. *Reading and Writing*, 1-24.

Choi, W., & Gordon, P. C. (2014). Word skipping during sentence reading: effects of lexicality on parafoveal processing. *Attention, Perception, & Psychophysics*, *76*(1), 201-213.

Christianson, K., Johnson, R. L., & Rayner, K. (2005). Letter transpositions within and across morphemes. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 31,* 1327–1339.

Clark, H. H. (1973). The language-as-fixed-effect fallacy: A critique of language statistics in psychological research. *Journal of verbal learning and verbal behaviour*, *12*(4), 335-359.

Clarke, P., Hulme, C., & Snowling, M. (2005). Individual differences in RAN and reading: A response timing analysis. *Journal of Research in Reading*, *28*(2), 73-86.

Clifton, C., Staub, A., & Rayner, K. (2007). Eye movements in reading words and sentences. *Eye movements: A window on mind and brain*, *27*, 341-372.

Cohen, R. L., Netley, C., & Clarke, M. A. (1984). On the generality of the short-term memory/reading ability relationship. *Journal of Reading Disabilities, 17,* 218-221.

Corbetta, M., Akbudak, E., Conturo, T., Snyder, A., Ollinger, J., Drury, H., et al. (1998). A common network of functional areas for attention and eye movements. *Neuron, 21,* 761–773.

Cornelissen, P. L., Hansen, P. C., Gilchrist, I. D., Cormack, F., Essex, J., & Frankish, C. (1998). Coherent motion detection and letter position encoding. *Vision Research*, *38*(14), 2181-2191.

Cornelissen, P. I., Hansen, P. C., Hutton, J. L., Evangelinou, V., & Stein, J. F. (1998). Magnocellular visual function and children's single word reading. *Vision Research, 38,* 471–482.

Cornelissen, P., Richardson, A., Mason, A., Fowler, S., & Stein, J. (1995). Contrast sensitivity and coherent motion detection measured at photopic luminance levels in dyslexics and controls. *Vision research*, *35*(10), 1483-1494.

Crovitz, H. F., & Daves, W. (1962). Tendencies to eye movement and perceptual accuracy. *Journal of Experimental Psychology*, *63*(5), 495.

Dare, N., & Shillcock, R. (2013). Serial and parallel processing in reading: Investigating the effects of parafoveal orthographic information on nonisolated word recognition. *The Quarterly Journal of Experimental Psychology*, *66*(3), 487-504.

Davis, C. J. (1999). *The self-organising lexical acquisition and recognition (SOLAR) model of visual word recognition. Dissertation Abstracts In- ternational: Section B: The Sciences and Engineering 62(1-B)*. Tesis doctoral no publicada, Universidad de New South Wales.

Davis, C. J. (2010). SOLAR versus SERIOL revisited. *European Journal of Cognitive Psychology, 22,* 695–724.

de Boer-Schellekens, L., & Vroomen, J. (2012). Sound can improve visual search in developmental dyslexia. *Experimental brain research*, *216*(2), 243-248.

De Luca, M., Borrelli, M., Judica, A., Spinelli, D., & Zoccolotti, P. (2002). Reading words and pseudowords: An eye movement study of developmental dyslexia. *Brain and language*, *80*(3), 617-626.

De Luca, M., Di Pace, E., Judica, A., Spinelli, D., & Zoccolotti, P. (1999). Eye movement patterns in linguistic and non-linguistic tasks in developmental surface dyslexia. *Neuropsychologia*, *37*(12), 1407-1420.

Deubel, H., & Schneider, W. X. (1996). Saccade target selection and object recognition: Evidence for a common attentional mechanism. *Vision research*, *36*(12), 1827-1837.

Deutsch, A., Frost, R., Pelleg, S., Pollatsek, A., & Rayner, K. (2003). Early morphological effects in reading: Evidence from parafoveal preview benefit in Hebrew. *Psychonomic Bulletin & Review, 10*, 415–422.

Deutsch, A., Frost, R., Pollatsek, A., & Rayner, K. (2000). Early morphological effects in word recognition in Hebrew: Evidence from parafoveal preview benefit. *Language and Cognitive Processes, 15,* 487–506.

Deutsch, A., Frost, R., Pollatsek, A., & Rayner, K. (2005). Morphological parafoveal preview benefit effects in reading: Evidence from Hebrew. *Language and Cognitive Processes, 20,* 341–371.

DeYoe, E. A., & Van Essen, D. C. (1988). Concurrent processing streams in monkey visual cortex. *Trends in Neuroscience, 11,* 219–226.

Drieghe, D., Brysbaert, M., Desmet, T., & De Baecke, G. (2004). Word skipping in reading: On the interplay of linguistic and visual factors. *European Journal of Cognitive Psychology, 16,* 79–103.

Drieghe, D., Cui, L., Yan, G., Bai, X., Chi, H., & Liversedge, S. P. (2017). The morphosyntactic structure of compound words influences parafoveal processing in Chinese reading. *The Quarterly Journal of Experimental Psychology*, 1-28.

Drieghe, D., Desmet, T., & Brysbaert, M. (2007). How important are linguistic factors in word skipping during reading? *British Journal of Psychology, 98,* 157 – 171.

Drieghe, D., Rayner, K., & Pollatsek, A. (2005). Eye movements and word skipping during reading revisited. *Journal of Experimental Psychology: Human Perception and Performance, 31*, 954–969.

Ducrot, S., Pynte, J., Ghio, A., & Lété, B. (2013). Visual and linguistic determinants of the eyes' initial fixation position in reading development. *Acta psychologica*, *142*(3), 287-298.

Ehri, L. C. (1997). Sight Word Learning in Normal Readers and Dyslexia. In B. Blachman (Eds.), *Foundations of Reading Acquisition and Dyslexia: Implications for Early Intervention* (pp. 163-189). Mahweh, NJ: Erlbaum.

Ehri, L. C. (2005). Learning to read words: Theory, findings, and issues. *Scientific Studies of Reading, 9,* 167–188.

Ehri, L. C. (2010). Development of Sight Word Reading: Phases and Findings. In M. Snowling & C. Hulme (Eds.), *The Science of Reading: A Handbook* (pp. 135–155). Malden, MA: Blackwell Publishing Ltd.

Ellis, A. W., McDougall, S. J., & Monk, A. F. (1996). Are dyslexics different? I. A comparison between dyslexics, reading age controls, poor readers and precocious readers. *Dyslexia*, *2*(1), 31-58.

Elman, J. L., Bates, E. A., Johnson, M. H., Karmiloff-Smith, A., Parisi, D., & Plunkett, K. (1996). *Rethinking innateness*. Cambridge, MA: MIT Press.

Engbert, R., Longtin, A., & Kliegl, R. (2002). A dynamical model of saccade generation in reading based on spatially distributed lexical processing. *Vision research*, *42*(5), 621-636.

Ehrlich, S. F., & Rayner, K. (1981). Contextual effects on word recognition and eye movements during reading. *Journal of Verbal Learning and Verbal Behaviour, 20,* 641–655.

Facoetti, A., Lorusso, M. L., Cattaneo, C., Galli, R., & Molteni, M. (2005). Visual and auditory attentional capture are both sluggish in children with developmental dyslexia. *Acta Neurobiologiae Experimentalis*, *65*(1), 61-72.

Facoetti, A., Paganoni, P., & Lorusso, M. L. (2000). The spatial distribution of visual attention in developmental dyslexia. *Experimental Brain Research, 132,* 531–538.

Facoetti, A., Paganoni, P., Turatto, M., Marzola, V., & Mascetti, G. G. (2000). Visual-spatial attention in developmental dyslexia. *Cortex*, *36*(1), 109-123.

Facoetti, A., Trussardi, A. N., Ruffino, M., Lorusso, M. L., Cattaneo, C., Galli, R., ... & Zorzi, M. (2010). Multisensory spatial attention deficits are predictive of phonological decoding skills in developmental dyslexia. *Journal of cognitive neuroscience*, *22*(5), 1011-1025.

Facoetti, A., Zorzi, M., Cestnick, L., Lorusso, M. L., Molteni, M., Paganoni, P., ... & Mascetti, G. G. (2006). The relationship between visuo-spatial attention and nonword reading in developmental dyslexia. *Cognitive Neuropsychology*, *23*(6), 841-855.

Farmer, M. E., & Klein, R. M. (1995). The evidence for a temporal processing deficit linked to dyslexia: A review. *Psychonomic Bulletin & Review, 2,* 460–493.

Fawcett, A. J., & Nicolson, R. I. (1995). Persistent deficits in motor skill of children with dyslexia. *Journal of Motor Behaviour*, *27*(3), 235-240.

Fawcett, A. J., & Nicolson, R. I. (1999). Performance of dyslexic children on cerebellar and cognitive tests. *Journal of motor behaviour*, *31*(1), 68-78.

Ferrera, V. P., Nealey, T. A., & Maunsell, J. H. (1992). Mixed parvocellular and magnocellular geniculate signals in visual area V4. *Nature, 358,* 756–761.

Findlay, J. M. (1981). Spatial and temporal factors in the predictive generation of saccadic eye movements. *Vision Research*, 21(3), 347 – 354.

Fisher, D. F., & Shebilske, W. L. (1985). There is more that meets the eye than the eyemind assumption. In R. Groner, G. W. McConkie, & C. Menz (Eds.), *Eye movements and human information processing* (pp. 149–158). Amsterdam: North Holland

Fletcher, J. M., Lyon, G. R., Fuchs, L. S., & Barnes, M. A. (2007). *Learning disabilities. From identification to intervention.* New York: Guilford Press.

Fletcher J.M., Shaywitz, S.E., Shankweiler, D.P., Katz, L., Liberman, I.Y., Stuebing, K.K., Francis, D.J., Fowler, A.E., & Shaywitz, B.A. (1994). Cognitive profiles of reading disability: Comparisons of discrepancy and low achievement definitions. *Journal of Educational Psychology, 86*, 6–23.

Flowers, L., Meyer, M., Lovato, J., Wood, F., & Felton, R. (2001). Does third grade discrepancy status predict the course of reading development?. *Annals of Dyslexia*, 49-71.

Forster, K. I., Davis, C., Schoknecht, C., & Carter, R. (1987). Masked priming with graphemically related forms: Repetition or partial activation? *Quarterly Journal of Experimental Psychology: Human Experimental Psychology, 39*(A)*,* 211–251.

Folk, J. R., & Morris, R. K. (1995). Multiple lexical codes in reading: Evidence from eye movements, naming time, and oral reading. *Journal of Experimental*

Psychology: Learning, Memory, and Cognition, 21, 1412–1429.

Franceschini, S., Gori, S., Ruffino, M., Viola, S., Molteni, M., & Facoetti, A. (2013). Action video games make dyslexic children read better. *Current Biology*, *23*(6), 462-466.

Francis, W., & Kučera, H. (1982). *Frequency analysis of English usage: Lexicon and grammar*. Boston: Houghton Mifflin.

Francis, D. J., Shaywitz, S. E., Stuebing, K. K., Shaywitz, B. A., & Fletcher, J. M. (1996). Developmental lag versus deficit models of reading disability: A longitudinal, individual growth curves analysis. *Journal of Educational psychology*, *88*(1), 3.

Frederickson, N., & Frith, U. (1998). Identifying dyslexia in bilingual children: A phonological approach with inner London Sylheti speakers. *Dyslexia*, *4*(3), 119-131.

Geiger, G., & Lettvin, J. Y. (1987). Peripheral vision in persons with dyslexia. *New England Journal of Medicine*, *316*(20), 1238-1243.

Geiger, G., Lettvin, J. Y., & Fahler, M. (1994). Dyslexic children learn a new visual strategy for reading: a controlled experiment. Vision Research, 34, 1223-1332.

Geiger, G., Lettvin, J. Y., & Zegarra-Moran, O. (1992). Task-determined strategies of visual process. *Cognitive Brain Research*, *1*(1), 39-52.

Gómez, P., Ratcliff, R., & Perea, M. (2008). The overlap model: A model of letter position coding. *Psychological Review, 115,* 577–600.

Gori, S., & Facoetti, A. (2015). How the visual aspects can be crucial in reading acquisition: The intriguing case of crowding and developmental dyslexia. *Journal of vision*, *15*(1), 8-8.

Gould, J. H., & Glencross, D. J. (1990). Do children with a specific reading-disability have a general serial ordering deficit? *Neuropsychologia, 28(3),* 271-278.

Greene, H. H., Pollatsek, A., Masserang, K., Lee, Y. J., & Rayner, K. (2010). Directional processing within the perceptual span during visual target localization. *Vision research*, *50*(13), 1274-1282.

Grainger, J., Bouttevin, S., Truc, C., Bastien, M., & Ziegler, J. (2003). Word superiority, pseudoword superiority, and learning to read: A comparison of dyslexic and normal readers. *Brain and Language*, *87*(3), 432-440.

Grainger, J., Granier, J. P., Farioli, F., Van Assche, E., & van Heuven, W. J. (2006).

Letter position information and printed word perception: The relative-position priming constraint. *Journal of Experimental Psychology: Human Perception and Performance*, *32*(4), 865.

Grainger, J., Lété, B., Bertand, D., Dufau, S., & Ziegler, J. C. (2012). Evidence for multiple routes in learning to read. *Cognition*, *123*(2), 280-292.

Grainger, I. J., & Van Heuven, W. J. B. (2003). Modeling letter position coding in printed word perception. In P. Bonin (Ed.), *Mental lexicon: "Some words to talk about words"* (pp. 1–23). Hauppauge, NY: Nova Science.

Grainger, J., & Ziegler, J. (2011). A dual-route approach to orthographic processing. *Frontiers in psychology*, *2*, 54.

Gresham, F. M., & Vellutino, F. R. (2010). What is the role of intelligence in the identification of specific learning disabilities? Issues and clarifications. *Learning Disabilities Research & Practice*, *25*(4), 194-206.

Griffiths, Y. M., & Snowling, M. J. (2002). Predictors of exception word and nonword reading in dyslexic children: The severity hypothesis. *Journal of Educational Psychology*, *94*(1), 34.

Gurka, M. J., & Edwards, L. J. (2011). Mixed models. In C. R. Rao, J. P Miller, &D. C. Rao (Eds.), *Essential Statistical Methods for Medical Statistics* (pp. 146-173). Amsterdam: Elsevier.

Häikiö, T., Bertram, R., & Hyönä, J. (2010). Development of parafoveal processing within and across words in reading: Evidence from the boundary paradigm. *The Quarterly Journal of Experimental Psychology: Human Experimental Psychology, 63,* 1982–1998.

Häikiö, T., Bertram, R., Hyönä, J., & Niemi, P. (2009). Development of the letter identity span in reading: Evidence from the eye movement moving window paradigm. *Journal of experimental child psychology*, *102*(2), 167-181.

Hari, R. (1995). Illusory directional hearing in humans. *Neuroscience Letters*, *189*(1), 29-30.

Hari, R., & Kiesilä, P. (1996). Deficit of temporal auditory processing in dyslexic adults. *Neuroscience letters*, *205*(2), 138-140.

Hari, R., & Renvall, H. (2001). Impaired processing of rapid stimulus sequences in dyslexia. *Trends in cognitive sciences*, *5*(12), 525-532.

Hari, R., Renvall, H., & Tanskanen, T. (2001). Left minineglect in dyslexic adults. *Brain*, *124*(7), 1373-1380.

Hari, R., Valta, M., & Uutela, K. (1999). Prolonged attentional dwell time in dyslexic adults. *Neuroscience letters*, *271*(3), 202-204.

Hatcher, P.J., & Hulme (1999). Phonemes, rhymes, and intelligence as predictors of children's responsiveness to remedial reading instruction: Evidence from a longitudinal intervention study. *Journal of Experimental Child Psychology, 72*, 130-153.

Hatzidaki, A., Gianneli, M., Petrakis, E., Makaronas, N., & Aslanides, I. M. (2011). Reading and visual processing in Greek dyslexic children: an eye-movement study. *Dyslexia*, *17*(1), 85-104.

Hawelka, S., Huber, C., & Wimmer, H. (2006). Impaired visual processing of letter and digit strings in adult dyslexic readers. *Vision research*, *46*(5), 718-723.

Hawelka, S., Gagl, B., & Wimmer, H. (2010). A dual-route perspective on eye movements of dyslexic readers. *Cognition*, *115*(3), 367-379.

Hawelka, S., & Wimmer, H. (2005). Impaired visual processing of multi-element arrays is associated with increased number of eye movements in dyslexic reading. *Vision Research*, *45*(7), 855-863.

Hawelka, S., & Wimmer, H. (2008). Visual target detection is not impaired in dyslexic readers. *Vision Research*, *48*(6), 850-852.

He, S., Cavanagh, P., & Intriligator, J. (1996). Attentional resolution and the locus of visual awareness. *Nature*, 383(6598), 334–337.

Helenius, P., Uutela, K., & Hari, R. (1999). Auditory stream segregation in dyslexic adults. *Brain*, *122*(5), 907-913.

Henderson, J. M., & Ferreira, F. (1990). Effects of foveal processing difficulty on the perceptual span in reading: Implications for attention and eye movement control. *Journal of Experimental Psychology: Learning, Memory and Cognition, 16,* 417–429.

Henderson, J. M., Pollatsek, A., & Rayner, K. (1989). Covert visual attention and extrafoveal information use during object identification. *Attention, Perception, & Psychophysics*, *45*(3), 196-208.

Ho, C. S. H., Chan, D. W. O., Lee, S. H., Tsang, S. M., & Luan, V. H. (2004). Cognitive profiling and preliminary subtyping in Chinese developmental dyslexia. *Cognition*, *91*(1), 43-75.

Hohenstein, S., & Kliegl, R. (2014). Semantic preview benefit during reading. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 40,* 166–190.

Hohenstein, S., Laubrock, J., & Kliegl, R. (2010). Semantic preview benefit in eye movements during reading: A parafoveal fast- priming study. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 36,* 1150–1170.

Hoskyn, M., & Swanson, H. L. (2000). Cognitive processing of low achievers and children with reading disabilities: A selective meta-analytic review of the published literature. *School Psychology Review*, *29*(1), 102.

Howard, D., & Best, W. (1996). Developmental phonological dyslexia: Real word reading can be completely normal. *Cognitive Neuropsychology*, *13*(6), 887-934.

Huestegge, L., Radach, R., Corbic, D., & Huestegge, S. M. (2009). Oculomotor and linguistic determinants of reading development: A longitudinal study. *Vision Research, 49,* 2948-2959.

Hulme, C., & Snowling, M. (2009). *Developmental disorders of language, learning and cognition.* Chichester, England: Wiley- Blackwell.

Hulme, C., & Snowling, M. J. (2013). Learning to read: What we know and what we need to understand better. *Child development perspectives*, *7*(1), 1-5.

Husain, M. (1991). Visuospatial and visuomotor functions of the posterior parietal lobe. In J. F. Stein (Ed.), *Vision and visual dyslexia* (pp. 13–43). London: Macmillan.

Hutzler, F., Kronbichler, M., Jacobs, A. M., & Wimmer, H. (2006). Perhaps correlational but not causal: No effect of dyslexic readers' magnocellular system on their eye movements during reading. *Neuropsychologia*, *44*(4), 637-648.

Hutzler, F., & Wimmer, H. (2004). Eye movements of dyslexic children when reading in a regular orthography. *Brain and language*, *89*(1), 235-242.

Hynd, G. W., & Cohen, M. J. (1983). *Dyslexia: Neuropsychological theory, research, and clinical differentiation.* New York: Grune & Stratton.

Hyönä, J. (1995). Do irregular letter combinations attract readers' attention? Evidence from fixation locations in words. *Journal of Experimental Psychology: Human Perception and Performance*, *21*(1), 68.

Hyönä, J. (2011). Foveal and parafoveal processing during reading. In S. P. Liversedge, I. D. Gilchrist, & S. Everling (Eds.), *Oxford handbook on eye movements* (pp. 819–838). Oxford: Oxford University Press.

Hyönä, J., & Olson, R. K. (1995). Eye fixation patterns among dyslexic and normal readers: effects of word length and word frequency. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *21*(6), 1430.

Iles, J., Walsh, V., & Richardson, A. (2000). Visual search performance in dyslexia. *Dyslexia*, *6*(3), 163-177.

Inhoff, A. W. (1984). Two stages of word processing during eye fixations in the reading of prose. *Journal of Verbal Learning and Verbal Behaviour, 23,* 612–624.

Inhoff, A. W. (1989). Parafoveal processing of words and saccade computation during eye fixations in reading. *Journal of Experimental Psychology: Human Perception and Performance, 15*, 544–555.

Inhoff, A. W., Pollatsek, A., Posner, M. I., & Rayner, K. (1989). Covert attention and eye movements during reading. *The Quarterly Journal of Experimental Psychology*, *41*(1), 63-89.

Inhoff, A., Radach, R., Eiter, B., & Juhasz, B. (2003). Distinct subsystems for the parafoveal processing of spatial and linguistic information during eye fixations in reading. *The Quarterly Journal of Experimental Psychology Section A*, *56*(5), 803-827.

Inhoff, A. W., & Rayner, K. (1986). Parafoveal word processing during eye fixations in reading: Effects of word frequency. *Perception & Psychophysics, 40,* 431–439.

Inhoff, A. W., & Weger, U. W. (2005). Memory for word location during reading: Eye movements to previously read words are spatially selective but not precise. *Memory & cognition*, *33*(3), 447-461.

Intriligator, J., & Cavanagh, P. (2001). The spatial resolution of visual attention. *Cognitive Psychology,* 43(3), 171–216.

Ishida, T., & Ikeda, M. (1989). Temporal properties of information extraction in reading studied by a text-mask replacement technique. *Journal of the Optical Society A: Optics and Image Science, 6,* 1624 – 1632.

Johnson, R. L., & Dunne, M. D. (2012). Parafoveal processing of transposed-letter words and nonwords: Evidence against parafoveal lexical activation. *Journal of Experimental Psychology: Human Perception and Performance, 38,* 191–212.

Johnson, R. L., & Eisler, M. E. (2012). The importance of the first and last letter in words during sentence reading. *Acta Psychologica, 141,* 336– 351.

Johnson, R. L., Perea, M., & Rayner, K. (2007). Transposed-letter effects in reading: Evidence from eye movements and parafoveal preview. *Journal of Experimental Psychology: Human Perception and Performance, 33*, 209–229.

Jones, M. W., Ashby, J., & Branigan, H. P. (2013). Dyslexia and fluency: parafoveal and foveal influences on rapid automatized naming. *Journal of Experimental Psychology: Human Perception and Performance*, *39*(2), 554.

Jones, M. W., Branigan, H. P., & Kelly, M. L. (2009). Dyslexic and nondyslexic reading fluency: Rapid automatized naming and the importance of continuous lists. *Psychonomic Bulletin & Review*, *16*(3), 567-572.

Jones, M. W., Branigan, H. P., Hatzidaki, A., & Obregon, M. (2010). Is the 'naming' deficit in dyslexia a misnomer? *Cognition, 116,* 56–70.

Jones, M. W., Obregón, M., Kelly, M. L., & Branigan, H. P. (2008). Elucidating the component processes involved in dyslexic and nondyslexic reading fluency: An eye-tracking study. *Cognition, 109,* 389–407.

Jorm, A. F. (1983). Specific reading retardation and working memory: A review. *British Journal of Psychology, 74*, 311-342.

Jordan, T. R., McGowan, V. A., & Paterson, K. B. (2014). Reading with filtered fixations: adult age differences in the effectiveness of low-level properties of text within central vision. *Psychology and aging*, *29*(2), 229.

Joseph, H. S. S. L., Liversedge, S. P., Blythe, H. I., White, S. J., & Rayner, K. (2009). Word length and landing position effects during reading in children and adults. *Vision Research, 49,* 2078-2086.

Juhasz, B. J., White, S. J., Liversedge, S. P., & Rayner, K. (2008). Eye movements and the use of parafoveal word length information in reading. *Journal of Experimental Psychology: Human Perception and Performance*, *34*(6), 1560.

Just, M.A. & Carpenter, P.A. (1980). A theory of reading - from eye fixations to comprehension. *Psychological Review, 87*, 329-354.

Karmiloff-Smith, A. (1998). Development itself is the key to understanding developmental disorders. *Trends in cognitive sciences*, *2*(10), 389-398.

Kelly, L. P., & Barac-Cikoja, D. (2007). The comprehension of skilled deaf readers: The roles of word recognition and other potentially critical aspects of competence. In J. Oakhill & K. Cain (Eds.), Children's comprehension problems in oral and written language: A cognitive perspective (pp. 244–

280). New York: Guilford Press.

Kennison, S. M., & Clifton, C. (1995). Determinants of parafoveal preview benefit in high and low working memory capacity readers: Implications for eye movement control. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 21,* 68–81.

Kirby, J. R., Georgiou, G. K., Martinussen, R., & Parrila, R. (2010). Naming speed and reading: From prediction to instruction. *Reading Research Quarterly*, *45*(3), 341-362.

Kirby, J. R., Parrila, R. K., & Pfeiffer, S. L. (2003). Naming speed and phonological awareness as predictors of reading development. *Journal of Educational Psychology*, *95*(3), 453.

Kirkby, J. A., Blythe, H. I., Drieghe, D., & Liversedge, S. P. (2011). Reading text increases binocular disparity in dyslexic children. *PLoS ONE, 6*(11), e27105.

Kirkby, J. A., Webster, L. A., Blythe, H. I., & Liversedge, S. P. (2008). Binocular coordination during reading and non-reading tasks. *Psychological Bulletin*, *134*(5), 742-763.

Klein, R.M. (1980). Does oculomotor readiness mediate cognitive control of visual attention? In Nickerson (Ed.), *Attention and performance VIII*. Hillsdale, NJ: Erlbaum.

Klein, R. M. (2002). Observations on the temporal correlates of reading failure. *Reading and Writing: An Interdisciplinary Journal, 15,* 207– 232.

Kliegl, R., & Engbert, R. (2005). Fixation durations before word skipping in reading. *Psychonomic Bulletin & Review, 12,* 132–138.

Kliegl, R., Risse, S., & Laubrock, J. (2007). Preview benefit and parafoveal-on-foveal effects from word n+ 2. *Journal of Experimental Psychology: Human Perception and Performance*, *33*(5), 1250.

Kohnen, S., & Castles, A. (2013). Pirates at parties: letter position processing in developing readers. *Journal of Experimental Child Psychology*, 115(1), 91-107.

Krause, M. B. (2015). Pay Attention!: sluggish multisensory attentional shifting as a core deficit in developmental dyslexia. *Dyslexia*, *21*(4), 285-303.

Kutner, M. H., Nachtsheim, C., Neter, J., & Li, W. (2005). *Applied linear statistical models*. Boston: McGraw-Hill Irwin.

Lallier, M., Donnadieu, S., Berger, C., & Valdois, S. (2010). A case study of developmental phonological dyslexia: Is the attentional deficit in the perception of rapid stimuli sequences amodal?. *Cortex*, *46*(2), 231-241.

Lallier, M., Donnadieu, S., & Valdois, S. (2013). Investigating the role of visual and auditory search in reading and developmental dyslexia. *Frontiers in human neuroscience*, *7*, 1-12.

Lennie, P., Trevarthen, C., Van Essen, D., & Wassle, H. (1990). Parallel processing of visual information. In L. Spillman & J. S. Werner (Eds.), *Visual perception: The neurophysiological foundations* (pp. 103–128). San Diego, CA: Academic Press.

Liberman, I. Y. (1973). Segmentation of the spoken word and reading acquisition. *Bulletin of the Orton Society, 23*, 65-76.

Lima, S. D., & Inhoff, A. W. (1985). Lexical access during eye fixations in reading: Effects of word-initial letter sequence. *Journal of Experimental Psychology: Human Perception and Performance, 11,* 272–285.

Liu, W., Inhoff, A. W., Ye, Y., & Wu, C. (2002). Use of parafoveally visible characters during the reading of Chinese sentences. *Journal of Experimental Psychology: Human perception and performance*, *28*(5), 1213.

Liversedge, S., Gilchrist, I., & Everling, S. (2011). *The Oxford handbook of eye movements*. Oxford: Oxford University Press.

Liversedge, S. P., & Findlay, J. M. (2000). Saccadic eye movements and cognition. *Trends in cognitive sciences*, *4*(1), 6-14.

Liversedge, S. P., Rayner, K., White, S. J., Vergilino-Perez, D., Findlay, J. M., & Kentridge, R. W. (2004). Eye movements when reading disappearing text: Is there a gap effect in reading? *Vision Research, 44,* 1013–1024.

Livingstone, M., & Hubel, D. (1988). Segregation of form, color, movement, and depth: Anatomy, physiology, and perception. *Science, 240,* 740 –749.

Lee, Y. A., Binder, K. S., Kim, J. O., Pollatsek, A., & Rayner, K. (1999). Activation of phonological codes during eye fixations in reading. *Journal of Experimental Psychology: Human Perception and Performance*, *25*(4), 948.

Lee, H. W., Kambe, G., Pollatsek, A., & Rayner, K. (2005). The lack of pseudohomophone priming effects with short durations in reading and naming. *Experimental Psychology*, *52*(4), 281.

Lee, H.-W., Rayner, K., & Pollatsek, A. (1999). The time course of phonological, semantic, and orthographic coding in reading: Evidence from the fast-priming technique. *Psychonomic Bulletin & Review, 6,* 624–634.

Leinenger, M. (2014). Phonological coding during reading. *Psychological bulletin*, *140*(6), 1534.

Lenhard, W., Lenhard, A., & Breitenbach, E. (2005). The neurobiological basis of developmental dyslexia - Current findings and areas of future research. In H. D. Tobias (Ed.), *Trends in dyslexia research (223-244)*. New York, Haupage: Nova-Science.

Lervåg, A., & Hulme, C. (2009). Rapid automatized naming (RAN) taps a mechanism that places constraints on the development of early reading fluency. *Psychological Science, 20,* 1040–1048.

Lété, B., & Ducrot, S. (2008). Visuo-attentional processing by dyslexic readers on the Reicher-Wheeler task. *Current psychology letters. Behaviour, brain & cognition*, *24*(1, 2008).

Lété, B., & Fayol, M. (2013). Substituted-letter and transposed-letter effects in a masked priming paradigm with French developing readers and dyslexics. *Journal of Experimental Child Psychology*, 114(1), 47-62.

Lorusso, M. L., Facoetti, A., Pesenti, S., Cattaneo, C., Molteni, M., & Geiger, G. (2004). Wider recognition in peripheral vision common to different subtypes of dyslexia. *Vision research*, *44*(20), 2413-2424.

Lovegrove, W. J., Bowling, A., Badcock, D., & Blackwood, M. (1980). Specific reading disability: differences in contrast sensitivity as a function of spatial frequency. *Science*, 210, 439–440.

Lovegrove, W., Martin, F., Bowling, A., Blackwood, M., Badcock, D., & Paxton, S. (1982). Contrast sensitivity functions and specific reading disability. *Neuropsychologia*, 20, 309–315.

MacKeben, M., Trauzettel-Klosinski, S., Reinhard, J., Dürrwächter, U., Adler, M., & Klosinski, G. (2004). Eye movement control during single-word reading in dyslexics. *Journal of Vision*, *4*(5), 4-4.

Masterson, J., Stuart, M., Dixon, M., & Lovejoy, S. (2010). Children's printed word database: Continuities and changes over time in children's early reading vocabulary. *British Journal of Psychology*, *101*(2), 221-242.

Martelli, M., Di Filippo, G., Spinelli, D., & Zoccolotti, P. (2009). Crowding, reading, and developmental dyslexia. *Journal of Vision*, *9*(4), 14-14.

Martin, F., & Lovegrove, W. (1984). The effects of field size and luminance on contrast sensitivity differences between specifically reading disabled and normal children. *Neuropsychologia*, 22, 73– 77.

Martin, F., & Lovegrove, W. (1988). Uniform-field flicker masking in control and specifically-disabled readers. *Perception*, 17, 203–214.

Marx, C., Hawelka, S., Schuster, S., & Hutzler, F. (2015). An incremental boundary study on parafoveal preprocessing in children reading aloud: Parafoveal masks overestimate the preview benefit. *Journal of Cognitive Psychology*, *27*(5), 549-561.

Marx, C., Hawelka, S., Schuster, S., & Hutzler, F. (2017). Foveal processing difficulty does not affect parafoveal preprocessing in young readers. *Scientific Reports*, *7*, 41602.

Marx, C., Hutzler, F., Schuster, S., & Hawelka, S. (2016). On the development of parafoveal preprocessing: Evidence from the incremental boundary paradigm. *Frontiers in psychology*, *7 (514)*.

Matin, E. (1974). Saccadic suppression: a review and an analysis. *Psychological bulletin*, *81*(12), 899.

Maunsell, J. H. R., Nealey, T. A., & De Priest, D. D. (1990). Magnocellular and parvocellular contributions to responses in the middle temporal visual area (MT) of the macaque monkey. *The Journal of Neuroscience, 10,* 3323–3334.

McAnally, K. I., & Stein, J. F. (1997). Scalp potentials evoked by amplitude-modulated tones in dyslexia. *Journal of Speech, Language, and Hearing Research*, *40*(4), 939-945.

McBride-Chang, C., Lam, F., Lam, C., Doo, S., Wong, S.W.L., & Chow, Y.Y.Y. (2008). Word recognition and cognitive profiles of Chinese pre-school children at risk for dyslexia through language delay or familial history of dyslexia. *Journal of Child Psychology and Psychiatry, 49,* 211–218.

McConkie, G. W. (1979). On the role and control of eye movements in reading. In *Processing of visible language* (pp. 37-48). Springer US.

McConkie, G. W., Kerr, P. W., Reddix, M. D., & Zola, D. (1988). Eye movement control during reading: I. The location of initial fixations in words. *Vision Research, 28,* 1107–1118.

McConkie, G. W., Kerr, P. W., Reddix, M. D., Zola, D., & Jacobs, A. M. (1989). Eye movement control during reading: II. Frequency of refixating a word. *Attention, Perception, & Psychophysics*, *46*(3), 245-253.

McConkie, G. W., & Rayner, K. (1975). The span of the effective stimulus during a fixation in reading. *Perception & Psychophysics*, *17*(6), 578-586.

McConkie, G. W., Zola, D., Grimes, J., Kerr, P. W., Bryant, N. R., & Wolff, P. M. (1991). Children's eye movements during reading. In J. F. Stein (Ed.), *Vision and visual dyslexia* (pp. 251-262). Boston: CRC Press.

McDonald, S. A., & Shillcock, R. C. (2004). The potential contribution of preplanned refixations to the preferred viewing location. *Perception and Psychophysics, 66(6)*, 1033–1044.

McDougall, S., Brunswick, N., & Davies, P. M. (2010). Reading and dyslexia in different orthographies: An introduction and overview. En N. Brunswick, S. McDougall, & P. M. Davies (Eds.), *Reading and dyslexia in different orthographies* (pp. 3-21). New York: Psychology Press.

McDougall, S., Hulme, C., Ellis, A., & Monk, A. (1994). Learning to read: The role of short-term memory and phonological skills. *Journal of Experimental Child Psychology,* 58, 112–133.

McLoughlin, D., Fitzgibbon, G., & Young, V. (1994). *Adult dyslexia: Assessment, counselling and training.* London: Whurr.

Melby-Lervåg, M., Lyster, S. A. H., & Hulme, C. (2012). Phonological skills and their role in learning to read: a meta-analytic review. *Psychological bulletin*, *138*(2), 322.

Merzenich, M. M., Schreiner, C., Jenkins, W., & Wang, X. (1993). Neural Mechanisms Underlying Temporal Integration, Segmentation, and Input Sequence Representation: Some Implications for the Origin of Learning Disabilities a. *Annals of the New York Academy of Sciences*, *682*(1), 1-22.

Miellet, S., O'Donnell, P. J., & Sereno, S. C. (2009). Parafoveal magnification: Visual acuity does not modulate the perceptual span in reading. *Psychological Science, 20,* 721–728.

Miellet, S., & Sparrow, L. (2004). Phonological codes are assembled before word fixation: Evidence from boundary paradigm in sentence reading. *Brain and Language, 90,* 299–310.

Miles, T. R. (1993). *Dyslexia: The pattern of difficulties (2nd Ed.).* London: Priory Press.

Milner, A. D. & Goodale, M. A. (1995). *The visual brain in action*. Oxford: Oxford University Press.

Mitchell, D. C., Shen, X., Green, M. J., & Hodgson, T. L. (2008). Accounting for regressive eye-movements in models of sentence processing: A reappraisal of the Selective Reanalysis hypothesis. *Journal of Memory and Language*, *59*(3), 266-293.

Moll, K., & Jones, M. (2013). Naming fluency in dyslexic and nondyslexic readers: Differential effects of visual crowding in foveal, parafoveal, and peripheral vision. *The Quarterly Journal of Experimental Psychology*, *66*(11), 2085-2091.

Moores, E., Cassim, R., & Talcott, J. B. (2011). Adults with dyslexia exhibit large effects of crowding, increased dependence on cues, and detrimental effects of distractors in visual search tasks. *Neuropsychologia*, *49*(14), 3881-3890.

Morris, R. K., Rayner, K., & Pollatsek, A. (1990). Eye movement guidance in reading: The role of parafoveal letter and space information. Journal of Experimental Psychology: Human Perception and Performance, 16, 268–281.

Morrison, R. E. (1984). Manipulation of stimulus onset delay in reading: evidence for parallel programming of saccades. *Journal of Experimental psychology: Human Perception and performance*, *10*(5), 667.

Morrison, R. E., & Rayner, K. (1981). Saccade size in reading depends upon character spaces and not visual angle. *Attention, Perception, & Psychophysics*, *30*(4), 395-396.

Murray, W. S., & Kennedy, A. (1988). Spatial coding in the processing of anaphor by good and poor readers: Evidence from eye movement analyses. *The Quarterly Journal of Experimental Psychology*, *40*(4), 693-718.

Nation, K., Adams, J. W., Bowyer-Crane, C. A., & Snowling, M. J. (1999). Working memory deficits in poor comprehenders reflect underlying language impairments. *Journal of experimental child psychology*, *73*(2), 139-158.

Nation, K., & Snowling, M. J. (1998). Individual differences in contextual facilitation: Evidence from dyslexia and poor reading comprehension. *Child development*, *69*(4), 996-1011.

Nelson, H. E., & Warrington, E. K. (1980). An investigation of memory functions in dyslexic children. *British Journal of Psychology*, *71*(4), 487-503.

Nuthmann, A., Engbert, R., & Kliegl, R. (2005). Mislocated fixations during reading and the inverted optimal viewing position effect. *Vision Research, 45,* 2201–2217.

O’Connor, R. E., & Forster, K. I. (1981). Criterion bias and search sequence bias in word recognition. *Memory & Cognition, 9,* 78–92.

Olson, R. K., Conners, E. A., & Rack, J. E. (1991). Eye movements in dyslexia and normal readers. In J. E. Stein (Ed.), *Vision and visual dyslexia* (pp. 243–250). London: Macmillan.

Orton, S. T. (1937). *Reading, writing and speech problems in children.* New York: WW Norton & Co.

O'Regan, J. K. (1979). Eye guidance in reading: evidence for linguistic control hypothesis. *Perception & Psychophysics, 25*, 501-509.

O'Regan, J. K. (1980). The control of saccade size and fixation duration in reading: The limits of linguistic control. *Perception & Psychophysics, 28*, 112 – 117.

O'Regan, J. K. (1990). Eye movements and reading. In E. Kowler (Ed.), *Eye movements and their role in visual and cognitive processes* (pp. 395 – 453). Amsterdam: Elsevier.

Pagán, A., Blythe, H. I., & Liversedge, S. P. (2016). Parafoveal preprocessing of word initial trigrams during reading in adults and children. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *42*(3), 411.

Pan, J., Yan, M., Laubrock, J., Shu, H., & Kliegl, R. (2014). Saccade-target selection of dyslexic children when reading Chinese. *Vision research*, *97*, 24-30.

Palmer, S. E. (2000). Phonological recoding deficit in working memory of dyslexic teenagers. *Journal of Research in Reading, 23(1)*, 28-40.

Pammer, K., Lavis, R., Hansen, P., & Cornelissen, P. L. (2004). Symbol-string sensitivity and children's reading. *Brain and language*, *89*(3), 601-610.

Pammer, K., Lavis, R., Cooper, C., Hansen, P. C., & Cornelissen, P. L. (2005). Symbol-string sensitivity and adult performance in lexical decision. *Brain and Language*, *94*(3), 278-296.

Pammer, K., & Wheatley, C. (2001). Isolating the M (y)-cell response in dyslexia using the spatial frequency doubling illusion. *Vision research*, *41*(16), 2139-2147.

Parrila, R., Kirby, J. R., & McQuarrie, L. (2004). Articulation rate, naming speed, verbal short-term memory, and phonological awareness: Longitudinal predictors of early reading development? *Scientific Studies of Reading, 8,* 3–26.

Paterson, K. B., McGowan, V. A., White, S. J., Malik, S., Abedipour, L., & Jordan, T. R. (2014). Reading direction and the central perceptual span in Urdu and English. *PloS one*, *9*(2), e88358.

Paterson, K. B., Read, J., McGowan, V. A., & Jordan, T. R. (2015). Children and adults both see 'pirates' in 'parties': letter-position effects for developing readers and skilled adult readers. *Developmental science*, *18*(2), 335-343.

Pelli, D. G., Farell, B., & Moore, D. C. (2003). The remarkable inefficiency of word recognition. *Nature*, *423*(6941), 752-756.

Pennington, B.F. (2006). From single to multiple deficit models of developmental disorders. *Cognition, 101,* 385–413.

Pennington, B. F. (2009). *Diagnosing learning disorders: A neuropsychological framework.* New York: Guilford Press.

Pennington, B. F., & Lefly, D. L. (2001). *Early reading development in children at family risk for dyslexia. Child development, 72(3),* 816-833.

Pennington, B.F., & Olson, R.K. (2005). Genetics of dyslexia. *In* M.J. Snowling, & C. Hulme *(Eds.), The science of reading: A handbook* (pp. *453–472*). Oxford: Blackwell.

Pennington, B. F., Santerre–Lemmon, L., Rosenberg, J., MacDonald, B., Boada, R., Friend, A., ... & Olson, R. K. (2012). Individual prediction of dyslexia by single versus multiple deficit models. *Journal of abnormal psychology*, *121*(1), 212.

Perea, M., & Acha, J. (2009). Space information is important for reading. *Vision Research*, *49*(15), 1994-2000.

Perea, M., & Estévez, A. (2008). Transposed-letter similarity effects in naming pseudowords: Evidence from children and adults. *European Journal of Cognitive Psychology*, *20*(1), 33-46.

Perea, M., & Fraga, I. (2006). Transposed-letter and laterality effects in lexical decision. *Brain and Language, 97,* 102–109.

Perea, M., & Lupker, S. J. (2003a). Does jugde activate COURT? Transposed-letter similarity effects in masked associative priming. *Memory & Cognition, 31,* 829–841.

Perea, M., & Lupker, S. J. (2003b). Transposed-letter confusability effects in masked form priming. In S. Kinoshita & S. J. Lupker (Eds.), *Masked priming: The state of the art* (pp. 97–120). New York: Psychology Press.

Perea, M., & Lupker, S. J. (2004). Can CANISO activate CASINO? Transposed-letter similarity effects with nonadjacent letter positions. *Journal of Memory and Language, 51,* 231–246.

Perea, M., & Lupker, S. J. (2007). The role of external letter positions in visual word recognition. *Psicothema*, *19*(4), 559-564.

Perea, M., Panadero, V., Moret-Tatay, C., & Gómez, P. (2012). The effects of inter-letter spacing in visual-word recognition: Evidence with young normal readers and developmental dyslexics. *Learning and Instruction*, *22*(6), 420-430.

Perfetti, C. (2007). Reading ability: Lexical quality to comprehension. *Scientific studies of reading*, *11*(4), 357-383.

Perfetti, C. A., & Hart, L. (2001). The lexical basis of comprehension skill. In D. S. Gorfein (Ed.), *On the consequences of meaning selection: Perspectives on resolving lexical ambiguity* (pp. 67–86). Washington, DC: American Psychological Association.

Perfetti, C. A., & Hart, L. (2002). The lexical quality hypothesis. *Precursors of functional literacy, 11,* 189–214.

Perin, D. (1983). Phonemic segmentation and spelling. *British journal of Psychology*, *74*(1), 129-144.

Pernet, C., Valdois, S., Celsis, P., & Démonet, J. F. (2006). Lateral masking, levels of processing and stimulus category: A comparative study between normal and dyslexic readers. *Neuropsychologia*, *44*(12), 2374-2385.

Perry, C., Ziegler, J. C., & Zorzi, M. (2007). Nested incremental modeling in the development of computational theories: The CDP+ model of reading aloud. *Psychological Review, 114*, 273–315.

Peterson, R. L., & Pennington, B. F. (2015). Developmental dyslexia. *Annual review of clinical psychology*, *11*, 283-307.

Petrov, Y., & Meleshkevich, O. (2011a). Asymmetries and idiosyncratic hot spots in crowding. *Vision Research,* 51, 1117–1123.

Petrov, Y., & Meleshkevich, O. (2011b). Locus of spatial attention determines inward-outward an- isotropy in crowding. *Journal of Vision*, 11, 1– 11.

Pinheiro, J. C. & Bates, D. M. (2000). *Mixed-effects models in S and S-Plus. Statistics and Computing.* Springer, Verglag, New York.

Pollatsek, A., Bolozky, S., Well, A. D., & Rayner, K. (1981). Asymmetries in the perceptual span for Israeli readers. *Brain and language*, *14*(1), 174-180.

Pollatsek, A., Lesch, M., Morris, R. K., & Rayner, K. (1992). Phonological codes are used in integrating information across saccades in word identification and reading. *Journal of Experimental Psychology: Human Perception and Performance, 18,* 148–162.

Pollatsek, A., & Rayner, K. (1982). Eye movement control during reading: The role of word boundaries. *Journal of Experimental Psychology: Human Perception and Performance, 8,* 817–833.

Pollatsek, A., Rayner, K., & Balota, D. A. (1986). Inferences about eye movement control from the perceptual span in reading. *Perception & Psychophysics, 40,* 123–130.

Pollatsek, A., Reichle, E. D., & Rayner, K. (2006). Tests of the EZ Reader model: Exploring the interface between cognition and eye-movement control. *Cognitive Psychology*, *52*(1), 1-56.

Pollatsek, A., Tan, L. H., & Rayner, K. (2000). The role of phonological codes in integrating information across saccadic eye movements in Chinese character identification. *Journal of Experimental Psychology: Human Perception and Performance, 26*, 607–633.

Posner, M. (1995). Attention in cognitive neurosciences: An overview. In M. S. Gazzaniga (Ed.), *The cognitive neurosciences* (pp. 615–624). Cambridge: MIT Press.

Powell, D., Stainthorp, R., Stuart, M., Garwood, H., & Quinlan, P. (2007). An experimental comparison between rival theories of rapid automatized naming performance and its relationship to reading. *Journal of Experimental Child Psychology, 98,* 46–68.

Prado, C., Dubois, M., & Valdois, S. (2007). The eye movements of dyslexic children during reading and visual search: impact of the visual attention span. *Vision research*, *47*(19), 2521-2530.

Raaijmakers, J. G., Schrijnemakers, J. M., & Gremmen, F. (1999). How to deal with "the language-as-fixed-effect fallacy": Common misconceptions and alternative solutions. *Journal of Memory and language*, *41*(3), 416-426.

Rack, J. P. (1985). Orthographic and phonetic coding in developmental dyslexia. *British Journal of Psychology*, *76*(3), 325-340.

Radach, R., & Kennedy, A. (2013). Eye movements in reading: Some theoretical context. *The Quarterly Journal of Experimental Psychology*, *66*(3), 429-452.

Radach, R., Inhoff, A., & Heller, D. (2004). Orthographic regularity gradually modulates saccade amplitudes in reading. *European Journal of Cognitive Psychology*, *16*(1-2), 27-51.

Ramus, F. (2003). Developmental dyslexia: Specific phonological deficit or general sensorimotor dysfunction? *Current Opinion in Neurobiology, 13*, 212–218.

Ramus, F., & Ahissar, M. (2012). Developmental dyslexia: The difficulties of interpreting poor performance, and the importance of normal performance. *Cognitive Neuropsychology*, *29*(1-2), 104-122.

Rastle, K., & Brysbaert, M. (2006). Masked phonological priming effects in English: Are they real? Do they matter?.*Cognitive Psychology*, *53*(2), 97-145.

Rayner, K. (1975). The perceptual span and peripheral cues in reading. *Cognitive Psychology, 7,* 65–81.

Rayner, K. (1977). Visual attention in reading: Eye movements reflect cognitive processes. *Memory & Cognition, 5*, 443–448.

Rayner, K. (1978). Eye movements in reading and information processing. *Psychological Bulletin, 85*, 618-660.

Rayner, K. (1979). Eye guidance in reading: Fixation locations within words. *Perception*, *8*(1), 21-30.

Rayner, K. (1985a). The role of eye movements in learning to read and reading disability. *Remedial and Special Education, 6,* 53-60.

Rayner, K. (1985b). Do faulty eye movements cause dyslexia? *Developmental Neuropsychology*, *1*(1), 3-15.

Rayner, K. (1986). Eye movements and the perceptual span in beginning and skilled readers. *Journal of Experimental Child Psychology, 41,* 211-236.

Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological bulletin*, *124*(3), 372.

Rayner, K. (2009). Eye movements and attention in reading, scene perception, and visual search. *The quarterly journal of experimental psychology*, *62*(8), 1457-1506.

Rayner, K., Ardoin, S. P., & Binder, K. S. (2013). Children's eye movements in reading: A commentary. *School Psychology Review*, *42*(2), 223.

Rayner, K., & Bertera, J. H. (1979). Reading without a fovea. *Science*, *206*(4417), 468-469.

Rayner, K., Binder, K. S., Ashby, J., & Pollatsek, A. (2001). Eye movement control in reading: Word predictability has little influence on initial landing positions in words. *Vision Research, 41,* 943–954.

Rayner, K., & Duffy, S. A. (1986). Lexical complexity and fixation times in reading: Effects of word frequency, verb complexity, and lexical ambiguity. *Memory*

& Cognition, 14, 191–201.

Rayner, K., Fischer, M. H., & Pollatsek, A. (1998). Unspaced text interferes with both word identifi- cation and eye movement control. Vision Research, 38, 1129–1144.

Rayner, K., Inhoff, A. W., Morrison, R. E., Slowiaczek, M. L., & Bertera, J. H. (1981). Masking of foveal and parafoveal vision during eye fixations in reading. *Journal of Experimental Psychology: Human perception and performance*, *7*(1), 167.

Rayner, K., Juhasz, B., Ashby, J., & Clifton, C. (2003). Inhibition of saccade return in reading. *Vision Research*, *43*(9), 1027-1034.

Rayner, K., & Liversedge, S. (2011). Linguistic and cognitive influences on eye movements during reading. In S. P. Liversedge, I. D . Gilchrist, & S. Everling (Eds.), *The Oxford handbook of eye movements* (pp. 751-766). Oxford, UK: Oxford University Press.

Rayner, K., Liversedge, S. P., & White, S. J. (2006). Eye movements when reading disappearing text: The importance of the word to the right of fixation. *Vision Research, 46,* 310–323.

Rayner, K., Liversedge, S. P., White, S. J., & Vergilino-Perez, D. (2003a). Reading disappearing text cognitive control of eye movements. *Psychological science*, *14*(4), 385-388.

Rayner, K., & McConkie, G. W. (1976). What guides a reader's eye movements? *Vision Research, 16,* 829-837.

Rayner, K., McConkie, G. W., & Ehrlich, S. (1978). Eye movements and integrating information across fixations. *Journal of Experimental Psychology: Human Perception and Performance*, *4*(4), 529.

Rayner, K., McConkie, G. W., & Zola, D. (1980). Integrating information across eye movements. *Cognitive Psychology, 12*, 206–226.

Rayner, K., Murphy, L. A., Henderson, J. M., & Pollatsek, A. (1989). Selective attentional dyslexia. *Cognitive Neuropsychology*, *6*(4), 357-378.

Rayner, K., & Pollatsek, A. (1981). Eye movement control during reading: Evidence for direct control. *The Quarterly journal of experimental psychology*, *33*(4), 351-373.

Rayner, K., & Pollatsek, A. (1996). Reading unspaced text is not easy: Comments on the implications of Epelboim et al.'s study for models of eye movement control in reading. *Vision Research, 36,* 461 – 465.

Rayner, K., & Raney, G. E. (1996). Eye movement control in reading and visual search: Effects of word frequency. *Psychonomic Bulletin & Review, 3,* 245-248.

Rayner, K., Sereno, S. C., Lesch, M. F., & Pollatsek, A. (1995). Phonological codes are automatically activated during reading: Evidence from an eye movement priming paradigm. *Psychological Science*, *6*(1), 26-32.

Rayner, K., Sereno, S. C., & Raney, G. E. (1996). Eye movement control in reading: comparison of two types of models. *Journal of Experimental Psychology: Human Perception and Performance, 22*, 1188 – 1200.

Rayner, K., & Schotter, E. R. (2014). Semantic preview benefit in reading English: The effect of initial letter capitalization. *Journal of Experimental Psychology: Human Perception and Performance, 40,* 1617–1628.

Rayner, K., & Well, A. D. (1996). Effects of contextual constraint on eye movements in reading: A further examination. *Psychonomic Bulletin & Review, 3,* 504 – 509.

Rayner, K., Well, A. D., Pollatsek, A., & Bertera, J. H. (1982). The availability of useful information to the right of fixation in reading. *Perception & Psychophysics, 31,* 537–550.

Rayner, K., White, S. J., Johnson, R. L., & Liversedge, S. P. (2006). Raeding wrods with jubmled lettres there is a cost. *Psychological science*, *17*(3), 192-193.

Rayner, K., White, S. J., Kambe, G., Miller, B., & Liversedge, S. P. (2003). On the processing of meaning from parafoveal vision during eye fixation in reading. In J. Hyönä, R. Radach, & H. Deubel (Eds.), *The mind's eye: Cognitive and applied aspects of eye movements* (pp. 213 – 234). Amsterdam: Elsevier Science.

Reichle, E. D., Liversedge, S. P., Drieghe, D., Blythe, H. I., Joseph, H. S., White, S. J., & Rayner, K. (2013). Using EZ Reader to examine the concurrent development of eye-movement control and reading skill. *Developmental Review*, *33*(2), 110-149.

Reichle, E. D., Pollatsek, A., Fisher, D. L., & Rayner, K. (1998). Toward a model of eye movement control in reading. *Psychological review*, *105*(1), 125.

Reichle, E. D., Rayner, K., & Pollatsek, A. (2003). The E-Z Reader model of eye-movement control in reading: Comparisons to other models. *Behavioural and Brain Sciences, 26,* 445–476.

Remington, R. W. (1980). Attention and saccadic eye movements. *Journal of Experimental Psychology: Human Perception and Performance*, *6*(4), 726.

Reynolds, M., & Besner, D. (2006). Reading aloud is not automatic: Processing capacity is required to generate a phonological code from print. *Journal of Experimental Psychology: Human Perception and Performance, 32,*1303–1323.

Rice, M., & Brooks, G. (2004). *Developmental dyslexia in adults: A research review.* London: National Research and Development Centre for Adult Literacy and Numeracy.

Roodenrys, S., & Stokes, J. (2001). Serial recall and nonword repetition in reading disabled children. *Reading and Writing: An Interdisciplinary Journal, 14,* 379-394.

Rose, S. A., Feldman, J. F., Jankowski, J. J., & Futterweit, L. R. (1999). Visual and auditory temporal processing, cross-modal transfer, and reading. *Journal of Learning Disabilities, 32(3),* 256-266.

Rosen, A. C., Rao, S. M., Caffarra, P., Scaglioni, A., Bobholz, J. A., Woodley, S. J., ... & Binder, J. R. (1999). Neural basis of endogenous and exogenous spatial orienting: a functional MRI study. *Journal of cognitive Neuroscience*, *11*(2), 135-152.

Ruffino, M., Trussardi, A. N., Gori, S., Finzi, A., Giovagnoli, S., Menghini, D., ... & Facoetti, A. (2010). Attentional engagement deficits in dyslexic children. *Neuropsychologia*, *48*(13), 3793-3801.

Rutter, M., & Yule, W. (1975). The concept of specific reading retardation. *Journal of Child Psychology and Psychiatry*, *16*(3), 181-197.

Sattler, J. M. (1988). *Assessment of children* (3rd ed.). San Diego, CA: J. M. Sattler.

Scarborough, H. S. (1990). Very early language deficits in dyslexic children. *Child Development, 61, 1728*-1734.

Scarborough, H. S. (1998). Early identification of children at risk for reading disabilities: Phonological awareness and some other promising predictors. In B. K. Shapiro, P. J. Accardo, & A. J. Capute (Eds.), *Specific reading disability: A view of the spectrum* (pp. 75-119). Maryland: York Press.

Schotter, E. R. (2013). Synonyms provide semantic preview benefit in English. *Journal of Memory and Language, 69,* 619–633.

Schotter, E. R., Angele, B., & Rayner, K. (2012). Parafoveal processing in reading. *Attention, Perception, & Psychophysics*, *74*(1), 5-35.

Schotter, E. R., Lee, M., Reiderman, M., & Rayner, K. (2015). The effect of contextual constraint on parafoveal processing in reading. *Journal of Memory and Language, 83,* 118–139.

Sereno, S. C., & Rayner, K. (2000). The when and where of reading in the brain. *Brain and Cognition*, *42*(1), 78-81.

Schoonbaert, S., & Grainger, J. (2004). Letter position coding in printed word perception: Effects of repeated and transposed letters. *Language and Cognitive Processes, 19,* 333–367.

Schustack, M. W., Ehrlich, S. F., & Rayner, K. (1987). Local and global sources of contextual facilitation in reading. *Journal of Memory and Language, 26,* 322 – 340.

Shankweiler, D.P., Liberman, I.Y., Mark, L.S., Fowler, C.A., & Fischer, F.W. (1979). The speech code and learning to read. *Journal of Experimental Psychology: Human Learning and Memory, 5,* 531–545.

Shapley, R. (1990). Visual sensitivity and parallel retinocortical channels. *Annual Review of Psychology, 41,* 635–658.

Share, D.L., & Stanovich, K.E. (1995). Cognitive processes in early reading development: Accommodating individual differences into a model of acquisition. *Issues in Education: Contributions from Educational Psychology, 1,* 1–57.

Shaywitz, S. E. (1998). Dyslexia. *New England Journal of Medicine*, *338*(5), 307-312.

Shaywitz, B. A., Fletcher, J. M., Holahan, J. M., & Shaywitz, S. E. (1992). Discrepancy compared to low achievement definitions of reading disability: Results from the Connecticut Longitudinal Study. *Journal of Learning Disabilities*, *25*(10), 639-648.

Shaywitz, S. E., & Shaywitz, B. A. (2005). Dyslexia (specific reading disability). *Biological Psychiatry*, 57, 1301-1309.

Shepherd, M., Findlay, J. M., & Hockey, R. J. (1986). The relationship between eye movements and spatial attention. *The Quarterly Journal of Experimental Psychology*, *38*(3), 475-491.

Silva, S., Faísca, L., Araújo, S., Casaca, L., Carvalho, L., Petersson, K. M., & Reis, A. (2016). Too little or too much? Parafoveal preview benefits and parafoveal load costs in dyslexic adults. *Annals of dyslexia*, *66*(2), 187-201.

Skottun, B. C. (2000). The magnocellular deficit theory of dyslexia: The evidence from contrast sensitivity. *Vision Research, 40,* 111–127.

Skottun, B. C. (2001). Is dyslexia caused by a visual deficit? *Vision Research, 41,* 3069–3071.

Skottun, B. C. & Skoyles, J. (2007). Dyslexia and rapid visual processing: A commentary. *Journal of Clinical and Experimental Neuropsychology, 30*, 666-673.

Slattery, T. J., Angele, B., & Rayner, K. (2011). Eye movements and display change detection during reading. *Journal of Experimental Psychology: Human Perception and Performance*, *37*(6), 1924.

Smith, P. F. (2012). A note on the advantages of using linear mixed model analysis with maximal likelihood estimation over repeated measures ANOVAs in psychopharmacology: comment on Clark et al.(2012). *Journal of Psychopharmacology*, *26*(12), 1605-1607.

Smith-Spark, J. H., Fisk, J. E., Fawcett, A. J., & Nicolson, R. I. (2003). Central executive impairments in adult dyslexics: Evidence from visuospatial working memory performance. *European Journal of Cognitive Psychology, 15(4),* 567-587.

Snowling, M. J. (1995). Phonological processing and developmental dyslexia. *Journal of research in reading*, *18*(2), 132-138.

Snowling, M.J. (2000). *Dyslexia*. Oxford: Blackwell.

Snowling, M. J. (2008). Specific disorders and broader phenotypes: The case of dyslexia. *The Quarterly Journal of Experimental Psychology*, *61*(1), 142-156.

Snowling, M.J., Gallagher, A., & Frith, U. (2003) Family risk of dyslexia is continuous: Individual differences in the precursors of reading skills. *Child Development, 74* (2), 358-373.

Snowling, M. J., & Hulme, C. (2012). Annual Research Review: The nature and classification of reading disorders–a commentary on proposals for DSM‐5. *Journal of Child Psychology and Psychiatry*, *53*(5), 593-607.

Sobotka, K. R., & May, J. G. (1977). Visual evoked potentials and reaction time in normal and dyslexic children. *Psychophysiology, 14,* 18–23.

Solan, H. A., Larson, S., Shelley-Tremblay, J., Ficarra, A., & Silverman, M. (2001). Role of visual attention in cognitive control of oculomotor readiness in students with reading disabilities. *Journal of Learning Disabilities*, *34*(2), 107-118.

Sparrow, L., & Miellet, S. (2002). Activation of phonological codes during reading: Evidence from errors detection and eye movements. *Brain and Language, 81*, 509–516.

Sperlich, A., Meixner, J., & Laubrock, J. (2016). Development of the perceptual span in reading: A longitudinal study. *Journal of experimental child psychology*, *146*, 181-201.

Sperlich, A., Schad, D. J., & Laubrock, J. (2015). When preview information starts to matter: Development of the perceptual span in German beginning readers. *Journal of Cognitive Psychology*, *27*(5), 511-530.

Spinelli, D., De Luca, M., Judica, A., & Zoccolotti, P. (2002). Crowding effects on word identification in developmental dyslexia. *Cortex*, *38*(2), 179-200.

Spragins, A. B., Lefton, L. A., & Fisher, D. F. (1976). Eye movements while reading spatially transformed text: A developmental study. *Memory & Cognition, 4*, 36–42.

Stanovich, K. E. (1980). Toward an interactive-compensatory model of individual differences in the development of reading fluency. *Reading research quarterly*, 32-71.

Stanovich, K. E. (1988). Explaining the differences between the dyslexic and the garden-variety poor reader: the phonological-core variable-difference model. *Journal of Learning Disabilities, 21*, 590-604.

Stanovich, K. E. (2005). The future of a mistake: Will discrepancy measurement continue to make the learning disabilities field a pseudoscience?. *Learning Disability Quarterly*, *28*(2), 103-106.

Stanovich, K.E., & Siegel, L.S. (1994). Phenotypic performance profile of children with reading disabilities: A regression-based test of the phonological-core variable-difference model. *Journal of Educational Psychology, 86,* 24–53.

Stein, J. (2001). The magnocellular theory of developmental dyslexia. *Dyslexia*, *7*(1), 12-36.

Stein, J. (2018a). What is developmental dyslexia? *Brain sciences*, *8*(2), 26.

Stein, J. F. (2018b). Does dyslexia exist? *Language, Cognition and Neuroscience*, *33*(3), 313-320.

Stein, J. F., & Walsh, V. (1997). To see but not to read; the magnocellular theory of dyslexia. *Trends in Neuroscience, 20,* 147–151.

Steinman, B. A., Steinman, S. B., & Garzia, R. P. (1996). Reading with an M neuron: How a defective magnocellular pathway interferes with normal reading. In

R. P. Garzia (Ed.), *Vision and reading* (pp. 209–228). St. Louis, MO: Mosby.

Steinman, S. B., Steinman, B. A., & Garzia, R. P. (1998). Vision and attention II: Is visual attention a mechanism through which a deficient magnocellular pathway might cause a reading disability? *Optometry & Vision Science, 75,* 674–681.

Stothard, S. E., & Hulme, C. (1995). A comparison of phonological skills in children with reading comprehension difficulties and children with decoding difficulties. *Journal of Child Psychology and Psychiatry*, *36*(3), 399-408.

Strasburger, H. (2005). Unfocused spatial attention underlies the crowding effect in indirect form vision. *Journal of Vision*, 5, 1024–1037.

Stuart, M. (1990). Processing strategies in a phoneme deletion task. *The Quarterly Journal of Experimental Psychology*, *42*(2), 305-327.

Stuebing, K. K., Barth, A. E., Molfese, P. J., Weiss, B., & Fletcher, J. M. (2009). IQ is not strongly related to response to reading instruction: A meta-analytic interpretation. *Exceptional Children*, *76*(1), 31-51.

Stuebing, K. K., Fletcher, J. M., LeDoux, J. M., Lyon, G. R., Shaywitz, S. E., & Shaywitz, B. A. (2002). Validity of IQ-discrepancy classifications of reading disabilities: A meta-analysis. *American Educational Research Journal*, *39*(2), 469-518.

Swanson, H. L., Ashbaker, M. H., & Lee, C. (1996). Learning-disabled readers' working memory as a function of processing demands. *Journal of Experimental Child Psychology, 61*, 242-275.

Taylor, S. E. (1965). Eye movements while reading: Facts and fallacies. *American Educational Research Journal, 2,* 187-202.

Taylor, E. A. (1966). *The fundamental reading skill.* Springfield, IL: Charles C. Thomas.

Taylor, S. E., Frackenpohl, H., & Pettee, J. L. (1960). *Grade level norms for the components of fundamental reading skill. EDL Research and Information Bulletin (Vol. 3).* Huntington, NY: Educational Development Laboratories.

Tiffin-Richards, S. P., & Schroeder, S. (2015). Children's and adults' parafoveal processes in German: Phonological and orthographic effects. *Journal of Cognitive Psychology*, 5(27), 531-548.

Torgesen, J.K., Wagner, R.K., & Rashotte, C.A. (1994). Longitudinal studies of phonological processing and reading. *Journal of Learning Disabilities, 27*, 276– 286.

Torgesen, J. K., Wagner, R. K., & Rashotte, C.A. (1999). *Test of word reading efficiency.* Austin, TX: PRO-ED Publishing, Inc.

Torppa, M., Parrila, R., Niemi, P., Lerkkanen, M. K., Poikkeus, A. M., & Nurmi, J. E. (2013). The double deficit hypothesis in the transparent Finnish orthography: a longitudinal study from kindergarten to Grade 2. *Reading and Writing*, *26*(8), 1353-1380.

Treiman, R., & Cassar, M. (1997). Can children and adults focus on sound as opposed to spelling in a phoneme counting task? *Developmental Psychology*, *33*(5), 771.

Tsai, J. L., Kliegl, R., & Yan, M. (2012). Parafoveal semantic information extraction in traditional Chinese reading. *Acta Psychologica, 141,* 17–23.

Tsai, J. L., Lee, C. Y., Tzeng, O. J., Hung, D. L., & Yen, N. S. (2004). Use of phonological codes for Chinese characters: Evidence from processing of parafoveal preview when reading sentences. *Brain and Language*, *91*(2), 235-244.

Vainio, S., Hyönä, J., & Pajunen, A. (2009). Lexical predictability exerts robust effects on fixation duration, but not on initial landing position during reading. *Experimental Psychology, 56,* 66–74.

Valdois, S., Bosse, M. L., & Tainturier, M. J. (2004). The cognitive deficits responsible for developmental dyslexia: Review of evidence for a selective visual attentional disorder. *Dyslexia*, *10*(4), 339-363.

Veldre, A., & Andrews, S. (2016a). Semantic preview benefit in English: Individual differences in the extraction and use of parafoveal semantic information. Journal of Experimental Psychology. *Learning, Memory, and Cognition, 42,* 837–854.

Veldre, A., & Andrews, S. (2018). Beyond cloze probability: Parafoveal processing of semantic and syntactic information during reading. *Journal of Memory and Language*, *100*, 1-17.

Vellutino, F.R. (1979). *Dyslexia: Theory and research.* Cambridge, MA: MIT Press.

Vellutino, F.R. (1987). Dyslexia. *Scientific American*, 1, 34–41.

Valdois, S., Bidet-Ildei, C., Lassus-Sangosse, D., Reilhac, C., N'guyen-Morel, M. A., Guinet, E., & Orliaguet, J. P. (2011). A visual processing but no phonological disorder in a child with mixed dyslexia. *Cortex*, *47*(10), 1197-1218.

Vellutino, F. R., Fletcher, J. M., Snowling, M. J., & Scanlon, D. M. (2004). Specific reading disability (dyslexia): what have we learned in the past four decades?. *Journal of child psychology and psychiatry*, *45*(1), 2-40.

Vellutino, F.R., & Scanlon, D.M. (1987a). Phonological coding, phonological awareness, and reading ability: Evidence from a longitudinal and experimental study. *Merrill-Palmer Quarterly, 33*, 321–363.

Vellutino, F.R., & Scanlon, D.M. (1987b). Linguistic coding and reading ability. In S. Rosenberg (Ed.), *Advances in applied psycholinguistics* (vol. 2, pp. 1–69). New York: Cambridge University Press.

Vellutino, F.R., Scanlon, D.M., & Chen, R. (1995a). The increasingly inextricable relationship between orthographic and phonological coding in learning to read: Some reservations about current methods of operationalizing orthographic coding. In V. Berninger (Ed.), *The varieties of orthographic knowledge II: Relationships to phonology reading, and writing* (pp. 47–111). Dordrecht: The Netherlands.

Vellutino, F.R., Scanlon, D.M., & Spearing, D. (1995b). Semantic and phonological coding in poor and normal readers. *Journal of Experimental Child Psychology, 59,* 76–123.

Vellutino, F.R., Scanlon, D.M., Sipay, E.R., Small, S.G., Pratt, A., Chen, R.S., & Denckla, M.B. (1996). Cognitive profiles of difficult to remediate and readily remediated poor readers: Early intervention as a vehicle for distinguishing between cognitive and experiential deficits as basic causes of specific reading disability. *Journal of Educational Psychology, 88,* 601–638.

Vellutino, F.R., Scanlon, D.M., & Tanzman, M.S. (1994). Components of reading ability: Issues and problems in operationalizing word identification, phonological coding, and orthographic coding. In G.R. Lyon (Ed.), *Frames of reference for the assessment of learning disabilities: New views on measurement issues* (pp. 279–324). Baltimore, MD: Paul H. Brookes.

Vergilino, D., & Beauvillain, C. (2000). The planning of refixation saccades in reading. *Vision Research, 40(25),* 3527–3538.

Vergilino, D., & Beauvillain, C. (2001). Reference frames in reading: Evidence from visually and memory-guided saccades. *Vision Research, 41(25–26),* 3547–3557.

Vergilino-Perez, D., Collins, T., & Dore-Mazars, K. (2004). Decision and metrics of refixations in reading isolated words. *Vision Research, 44(17),* 2009–2017.

Vidyasagar, T. R. (1999). A neuronal model of attentional spotlight: parietal guiding the temporal. *Brain Research Reviews*, *30*(1), 66-76.

Vidyasagar, T. R. (2001). From attentional gating in macaque primary visual cortex to dyslexia in humans. *Progress in Brain Research, 134,* 297–312.

Vidyasagar, T. R. (2004). Neural underpinnings of dyslexia as a disorder of visuo-spatial attention. *Clinical Experimental Optometry, 87,* 4–10.

Vidyasagar, T. R., & Pammer, K. (2010). Dyslexia: a deficit in visuo-spatial attention, not in phonological processing. *Trends in cognitive sciences*, *14*(2), 57-63.

Vignali, L., Hawelka, S., Hutzler, F., & Richlan, F. (2019). Processing of parafoveally presented words. An fMRI study. *NeuroImage*, *184*, 1-9.

Vitu, F. (1991). The influence of parafoveal processing and linguistic context on the optimal landing position effect. Perception & Psychophysics, 50, 58–75.

Vitu, F., McConkie, G. W., Kerr, P., & O'Regan, J. K. (2001). Fixation location effects on fixation durations during reading: An inverted optimal viewing position effect. *Vision Research*, *41*(25), 3513-3533.

Wagner, R.K., & Torgesen, J.K. (1987). The nature of phonological processing and its causal role in the acquisition of reading skills. *Psychological Bulletin, 101,* 192–212.

Wagner, R.K., Torgesen, J.K., & Rashotte, C.A. (1994). Development of reading-related phonological processing abilities: Evidence of bi-directional causality from a latent variable longitudinal study. *Developmental Psychology, 30*, 73–87.

Wagner, R., Torgesen, J., Rashotte, C., & Pearson, N.A. (2013). *Comprehensive Test of Phonological Processing* (2nd ed.). Austin, TX: Pro-Ed, Inc.

Walley, A. C. (1993). The role of vocabulary development in children′ s spoken word recognition and segmentation ability. *Developmental review*, *13*(3), 286-350.

Wechsler, D. (1999). *Wechsler Abbreviated Scale of Intelligence.* London: Harcourt Assessment.

Wechsler, D. (2005). *Wechsler Individual Achievement Test 2nd Edition (WIAT II).* London: The Psychological Corp.

Weger, U. W., & Inhoff, A. W. (2006). Attention and eye movements in reading:

Inhibition of return predicts the size of regressive saccades. *Psychological science*, *17*(3), 187-191.

Weger, U. W., & Inhoff, A. W. (2007). Long-range regressions to previously read words are guided by spatial and verbal memory. *Memory & Cognition*, *35*(6), 1293-1306.

West, B. T., Welch, K. B., & Galecki, A. T. (2014). *Linear mixed models: a practical guide using statistical software*. Boca Raton, FL: CRC Press.

Wolf, M., & Bowers, P. G. (1999). The double-deficit hypothesis for the developmental dyslexias. *Journal of Educational Psychology, 91,* 415– 438.

Wolf, M., Bowers, P. G., & Biddle, K. (2000). Naming-speed processes, timing, and reading: A conceptual review. *Journal of learning disabilities*, *33*(4), 387-407.

Wolf, M., & Denckla, M.B. (2005). *RAN/RAS: Rapid Automatized Naming and Rapid Alternating Stimulus Tests.* Austin, TX: Pro-Ed Publishing, Inc.

Wolf, M., & Obregón, M. (1992). Early naming deficits, developmental dyslexia, and a specific deficit hypothesis. *Brain & Language*, 42, 219-247.

White, S. J., Bertram, R., & Hyönä, J. (2008). Semantic processing of previews within compound words. *Journal of Experimental Psychology. Learning, Memory, and Cognition, 34,* 988–993.

White, S. J., Johnson, R. L., Liversedge, S. P., & Rayner, K. (2008). Eye movements when reading transposed text: the importance of word-beginning letters. *Journal of Experimental Psychology: Human Perception and Performance*, *34*(5), 1261.

White, S. J., & Liversedge, S. P. (2004). Orthographic familiarity influences initial eye positions in reading. *European Journal of Cognitive Psychology, 16*, 52–78.

White, S. J., & Liversedge, S. P. (2006a). Foveal processing difficulty does not modulate non-foveal orthographic influences on fixation positions. *Vision Research, 46,* 426–437.

White, S. J., & Liversedge, S. P. (2006b). Linguistic and nonlinguistic influences on the eyes' landing positions during reading. *Quarterly Journal of Experimental Psychology, 59,* 760–782.

White, S. J., Rayner, K., & Liversedge, S. P. (2005a). The influence of parafoveal word length and contextual constraint on fixation durations and word skipping in reading. *Psychonomic Bulletin & Review, 12,* 466–471.

White, S. J., Rayner, K., & Liversedge, S. P. (2005b). Eye movements and the modulation of parafoveal processing by foveal processing difficulty: A reexamination. *Psychonomic bulletin & review*, *12*(5), 891-896.

White, S. J., Warren, T., & Reichle, E. D. (2011). Parafoveal preview during reading: Effects of sentence position. *Journal of Experimental Psychology: Human Perception and Performance, 37*, 1221–1238.

Whitney, C. (2001). How the brain encodes the order of letters in a printed word: The SERIOL model and selective literature review. *Psychonomic Bulletin & Review, 8,* 221–243.

Whitney, C., & Cornelissen, P. (2005). Letter-position encoding and dyslexia. *Journal of Research in Reading, 28,* 274–301.

Williams, C. C., Perea, M., Pollatsek, A., & Rayner, K. (2006). Previewing the neighborhood: The role of orthographic neighbors as parafoveal previews in reading. *Journal of Experimental Psychology: Human Perception and Performance, 32,* 1072–1082.

Yan, M., Pan, J., Laubrock, J., Kliegl, R., & Shu, H. (2013). Parafoveal processing efficiency in rapid automatized naming: A comparison between Chinese normal and dyslexic children. *Journal of experimental child psychology*, *115*(3), 579-589.

Yan, M., Richter, E. M., Shu, H., & Kliegl, R. (2009). Readers of Chinese extract semantic information from parafoveal words. *Psychonomic Bulletin & Review, 16,* 561–566.

Yen, M.-H., Tsai, J.-L., Tzeng, O. J.-L., & Hung, D. L. (2008). Eye movements and parafoveal word processing in reading Chinese. *Memory & Cognition, 36,* 1033–1045.

Yeshurun, Y., & Rashal, E. (2010). Precueing attention to the target location diminishes crowding and reduces the critical distance. *Journal of Vision,* 10, 1–12.

Zevin, J. D., & Seidenberg, M. S. (2002). Age of acquisition effects in word reading and other tasks. *Journal of Memory and language*, *47*(1), 1-29.

Zhao, J., Liu, M., Liu, H., & Huang, C. (2018). Increased deficit of visual attention span with development in Chinese children with developmental dyslexia. *Scientific reports*, *8*(1), 3153.

Ziegler, J. C., & Goswami, U. (2005). Reading acquisition, developmental dyslexia, and skilled reading across languages: A psycholinguistic grain size theory. *Psychological Bulletin, 131*, 3–29.

Ziegler, J. C., Perry, C., & Coltheart, M. (2000). The DRC model of visual word recognition and reading aloud: An extension to German. *European Journal of Cognitive Psychology*, *12*(3), 413-430.

Ziegler, J. C., Stone, G. O., & Jacobs, A. M. (1997). What is the pronunciation for-ough and the spelling for/u/? A database for computing feedforward and feedback consistency in English. *Behaviour Research Methods*, *29*(4), 600-618.

Zoccolotti, P., De Luca, M., Di Pace, E., Gasperini, F., Judica, A., & Spinelli, D. (2005). Word length effect in early reading and in developmental dyslexia. *Brain and language*, *93*(3), 369-373.

Zoccolotti, P., De Luca, M., Di Pace, E., Judica, A., Orlandi, M., & Spinelli, D. (1999). Markers of developmental surface dyslexia in a language (Italian) with high grapheme–phoneme correspondence. *Applied Psycholinguistics*, *20*(2), 191-216.

Zoccolotti, P., De Luca, M., Lami, L., Pizzoli, C., Pontillo, M., & Spinelli, D. (2013). Multiple stimulus presentation yields larger deficits in children with developmental dyslexia: a study with reading and RAN-type tasks. *Child Neuropsychology*, *19*(6), 639-647.

Zorzi, M., Barbiero, C., Facoetti, A., Lonciari, I., Carrozzi, M., Montico, M., ... & Ziegler, J. C. (2012). Extra-large letter spacing improves reading in dyslexia. *Proceedings of the National Academy of Sciences*, *109*(28), 11455-11459.