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The Role of Positional Information during Reading in Children and Adults

by

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ABSTRACT

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Despite a large body of evidence investigating how letter-position information is encoded during lexical-processing during both isolated-word and reading paradigms, it is still not clear whether the mechanism to encode letter-position information is modulated by age and/or reading ability. The aim of the present research was to investigate developmental changes in letter-position encoding during reading. The first experiment investigated the influence of letter-position encoding on the time course of lexical and post-lexical processing during reading. It examined whether the prior exposure of a word's transposed-letter neighbour (TLN) earlier in the same sentence interfered with that word identification in skilled-adult-readers. Results showed that in skilled-readers, TLNs caused a target words' misidentification, triggering post-lexical strategies of checking. The second experiment investigated whether children extracted letter-position information independently from letter-identity information from the parafovea as adults do. Results showed that although children had longer reading times overall than adults, both adults and children pre-processed orthographic information from the parafovea and encoded letter-position information using a spatial coding mechanism. Finally, the third experiment examined whether children's reading ability influenced letter-position encoding during lexical-processing in reading. Adults, skilled and less-skilled child readers read sentences with words containing two letters-transposed (positions 1&2, 1&3 and 2&3). Results showed that words with transposed-letters in position 13 caused the most disruption to reading, while words with transposed-letters in position 23 caused the least disruption to reading in both adults and skilled child readers. Less skilled child readers showed that although they showed disruption when identifying transposed-letters nonwords, the cost did not vary systematically depending on the letter-position. This suggests that less skilled child readers with fewer, high-quality lexical representations were activating phonological codes for word identification via the fine-grained route. In contrast, both adults and skilled child readers with more, high quality lexical representations were activating orthographic codes for word identification via the coarse-grained route.

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DECLARATION OF AUTHORSHIP

I, Ascensión P. Pagán Camacho, declare that the thesis entitled 'The role of Positional Information during reading in children and adults" and the work presented in the thesis are both my own, and have been generated by me as the result of my own original research. I confirm that:

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Chapter 1: Introduction

1.1.Reading

Reading is a vital skill in modern societies. The importance of reading can hardly be exaggerated for a person's wellbeing in terms of academic success, employability and economic welfare. In addition, reading is essential in obtaining objective and independent information about important societal matters related to politics, economics and culture. Furthermore, it also facilitates the general cognitive development of readers (Cunningham & Stanovich, 1997).

Reading is a complex cognitive process that consists of learning the associations between sequences of printed letters (orthography), and their associated speech sounds (phonology) and meanings (semantics) in an efficient and precise manner. The aim of reading is comprehension; however, learning to decode the visual letter string is a critical aspect of word identification process, and this is the basis of text comprehension (Rayner, Foorman, Perfetti, Pesetsky & Seidenberg, 2001).

Although reading seems to be an effortless activity for skilled readers, it actually consumes a lot of cognitive resources. Firstly, the visual input needs to be identified as a sequence of letters (and not as a picture, for instance), creating an abstract orthographic representation of the string. The reader has to extract information about the identity and the position of each letter that appears in the sequence in order to access its orthographic, phonological and semantic representations, and to identify the word presented (e.g., the Dual Route model by Coltheart, Rastle, Perry, Ziegler & Langdon, 2001). Once the word identification process has been completed (the word meaning has been accessed), other higher order cognitive processes are required to be able to comprehend the sentence or the text. These higher order processes include syntactic analysis, semantic interpretation and elaborative inferences that enable developing a precise understanding of the sentence or the text (Pickering & Traxler, 1998; Traxler, Bybee & Pickering, 1997).

1.1.1. Acquisition of Reading

Reading is the result of a lengthy learning process. A large portion of this learning process takes place during childhood where the child acquires and develops the necessary knowledge and cognitive skills for becoming a skilled reader. Many models have proposed a number of phases of reading development (e.g., Ehri, 1998, 2002, 2005; Gough & Hillinger, 1980; Marsh, Friedman, Welch & Desberg, 1981; Mason, 1980). These phases describe a sequence of changes in reading behaviour as the child becomes more experienced in dealing with written text, until reading becomes fluent and skilled. It is assumed that most children pass through these phases but they are not biologically determined (Rayner, Pollatsek, Ashby & Clifton, 2012). The readers´ progression through the phases postulated by the various developmental reading models depends on two important events. First, the moment in which the reader is aware of the nature of the phoneme, creating an abstract representations (e.g., they have to learn that the phoneme /p/ is the same in “pale”, “carpet” and “hippopotamus” (Liberman, Cooper, Shankweiler & Studdert-Kennedy, 1967) and, second, the orthography-phonology consistency of the language (e.g., Katz & Frost, 1992; Kessler & Treiman, 2001; Seymour, Aro & Erskine, 2003; Share, 2008; Ziegler & Goswami, 2005).

The most recent and complete model of reading development phases is from Ehri (1998, 2002, 2005). She proposes four phases: pre-alphabetic, partial alphabetic, full alphabetic and consolidated alphabetic phases. During the *pre-alphabetic phase*, children only identify words as via salient visual features as a whole, for example, logos, labels or even, personal names, e.g., “the two sticks” in the word “yellow” (Gough & Hilliger, 1980). These children do not know the alphabet, so they are not aware of the letters included within words; thus, they only remember the visual shape of the string and fail to detect one letter change in common signs and labels in the environment (e.g., Masonheimer, Drum & Ehri, 1984). Only when children can use the sound of the letters to identify the word, the *partial alphabetic phase* begins. In this phase, children replace the visual context cues with phonetic cues such as using the letter name in order to read few words by sight (Ehri & Wilce, 1985; Scott & Ehri, 1990). Thus, they start to use letter information to read words although they often make semantic errors due to some words share the first letter (for example, *light* for *lamp*, *bang* for *blast*, *baby* for *bib*) (Ehri & Wilce, 1985; Scott & Ehri, 1990). The third phase, or the *full alphabetic phase,* accompanies the dramatic increase in children's vocabulary and the availability of increasingly cognitive processing capacity. In this phase, children use letter-sound correspondences to decode novel and nonsense words; however, they have difficulties in spelling irregular words. Finally, in the *consolidated alphabetic phase*, children are more sensitive to frequent letter sequences such as morphemes and syllables. As reading experience and instruction increase, the number of words stored in the lexicon increases, and readers are able to identify words in a more precise and efficient manner (Perfetti, 2007).

Although there are some differences between the models of reading development in alphabetic languages, all of them agree with the basic principle that written symbols have to be associated with phonemes (Perfetti, 1985), and this is the knowledge that makes reading more skilled and independent. The process of learning and applying the mapping between symbols and phonemes is called phonological recoding (Ehri, 1992; Share, 1995; Ziegler & Goswami, 2005). Then, with increased reading experience, word identification becames more efficient allowing the reader to access to the lexical representation directly from the orthography to the meaning, without using phonological information (see e.g., Coltheart *et al.*, 2001).

1.1.2. Reading Skill: Lexical Quality Hypothesis

As mentioned earlier, the efficiency of associating letters to phonemes will make reading more skilled and effortless, facilitating comprehension processes for understanding the meaning of the sentences or text. Perfetti (2007) emphasized the role of word knowledge in reading skill, proposing the Lexical Quality Hypothesis. He suggested that knowledge about a word form (orthography, phonology, grammatical class and meaning) and reading experience, allows word identification process to be fast and independent, resulting in efficient reading. In this theory, word identification depends on the quality of the lexical representation stored in memory.

The quality of the lexical representations depends on the amount of information that is fully specified. A high quality lexical representation refers to the fact that information related to orthography, phonology and meaning is precisely stored and is available at the same time, resulting in fast word identification. In contrast, a low quality lexical representation refers to the fact that at least one of these components is underspecified or missing, resulting in word identification become slow and effortful.

According to this theory, there is variability between and within readers in the average of the quality of words stored in the lexicon, resulting in both age and individual differences among readers.

Until now, most evidence for the role of lexical quality in reading skill comes from studies using isolated word paradigms in skilled adult readers (see Andrews, 2012 for a review). Although there are few studies using more natural sentence reading paradigms (Veldre & Andrews, 2014, 2015a, 2015b), it is not clear how lexical processing is affected by children's reading ability (reflecting the quality of their lexical representations) during sentence reading. Thus, a goal of the present research was to extend the individual differences approach adopted in skilled adult readers to children using natural sentence reading tasks.

1.2. Letter identity and position information encoding

The relevance of studying how letter identity and position information are encoded rely on two sources. First, how the lexicon is organized and, second, how lexical selection occurs during orthographic processing for word identification (Grainger, 2008 for a review). In general, any model of isolated word recognition addresses these two questions. They explicitly describe how an orthographic representation is encoded in terms of content (letter identity and position information), lexical access units (letters, graphemes, bigrams, syllables, morphemes…) and how lexical selection is achieved, especially between similar words in terms of orthographic information (e.g., *calm* and *clam*, *bake* and *cake*...).

Regarding lexical selection, visual word recognition models assume a competition process that takes place between similar lexical candidates. Here, I will focus only on orthographic similarity. The orthographic similarity between lexical candidates is defined by the amount of information shared between the visual input and the orthographic representations stored in the reader's lexicon. The definition of orthographic similarity between words can vary as a function of two important assumptions. First, the mechanism used to encode letter identity and position information. Some models propose that both letter identity and position information are encoded at the same time (strict letter position encoding, for example, the Interactive Activation model by McClelland & Rumelhart, 2001), resulting in a strict orthographic similarity definition as in Coltheart *et al.* (1977) such that words that can be created from another word by changing one single letter are considered as orthographic similar words or neighbours (e.g., "*bake* and *cake*"). In contrast, other models assume that letter identity is encoded independently from letter position information (flexible letter position encoding, for example the SOLAR model by Davis, 1999, 2010), resulting in a more flexible definition of orthographic similarity such as words that can be created from another word by transposing two letters are considered as orthographic neighbours (e.g., "*calm* and *clam*"). Second, the orthographic similarity concept can also vary as a function of the unit of lexical access proposed. Some models focus on individual letters (e.g., McClelland & Rumelhart, 2001) while other models focus on pairs of letters (bigrams) (e.g., Open Bigram models by Grainger, Grainer, Farioli, Van Assche & Van Heaven, 2006)

Although how letter identity and position information are encoded has been mainly investigated in single word identification paradigms, it has become an important research topic in natural reading research. In reading research, eye movements are measured, providing information about the time course of letter position encoding as a function of the location of the letters within the word during lexical processing in natural sentence reading (Acha & Perea, 2008b; Jonhson, Perea & Rayner, 2007; Johnson, 2009; Perea, Nakatani & van Leeuwen, 2011; Rayner, White, Johnson & Liversedge, 2006; White, Johnson, Liversedge & Rayner, 2008).

Recently, a large body of research has typically used transposed letter stimuli: words (e.g., *slime* and *smile*) and nonwords (e.g., *jugde*), which have two letters transposed, to study how letter identity and position information is encoded during lexical processing. The evidence that comes from nonword transposed letter stimuli is well-documented and solid (see Grainger, 2008; Frost, 2012 for reviews). It has typically found a facilitatory transposed letter effect, suggesting that transposed letter nonwords are able to activate their base words due to their high orthographic similarity (see Chapters 3 and 4).

The evidence from transposed letter words, however, is scarce and inconsistent due to the small number of words that can be created by transposing two letters (see Chapter 2).

In the following sections, a brief review about the findings using transposed letter stimuli and their theoretical implications are described.

1.2.1. Lexical Access

Empirical evidence based on transposed letter effect (see Grainger, 2008; Frost, 2012 for reviews) have shown that those nonwords which have been created by two adjacent or non-adjacent transposed letters (*jugde*) can activate their orthographic representation of the original word (*judge*); resulting in a reduction of word's identification time compared to when nonwords have been created by substituted letters (*junpe*) in isolated word identification paradigms (Perea & Lupker, 2003a; 2003b; see also Acha & Perea, 2008a; 2008b; 2010; Lupker, Perea & Davis, 2008; Perea & Estevez, 2008; Perea & Perez, 2009; Perea, Winskel & Ratitamkul, 2011; Schoonbaert & Grainger, 2004; Velan & Frost, 2011) and also in normal silent reading (see Acha & Perea, 2008; Johnson, Perea & Rayner, 2007; Johnson, 2009; Perea *et al.,* 2011; Rayner *et al.*, 2006; White *et al.*, 2008). This suggests that letter identity and position information are encoded independently, using a flexible letter position encoding mechanism. This finding challenges traditional models of isolated word recognition that assume that letter identity and position information are encoded at the same time, using a strict letter position encoding mechanism (e.g., McClelland & Rumelhart, 1981). As a consequence, new models of letter position encoding have been developed to account for this flexible letter position encoding mechanism, such as the SOLAR (Davis, 1999, 2010), the SERIOL (Whitney, 2001), the Open Bigram (Grainger et al., 2006; Grainger & Ziegler, 2011), and the Overlap (Gómez, Ratcliff & Perea, 2008) models (See Chapter 3 & 4 for a detailed description of these models).

The transposed letter effect is a very robust effect found in both adult and children (e.g. Acha & Perea, 2008a; Castles, Davis, Cavalot & Forster, 2007; Kohnen & Castles, 2013; Lété & Fayol, 2012; Perea & Estévez, 2008). Indeed, these studies showed that children are able to encode letter position information independently from letter identity information as adults do. The only difference found between adults and children is that the size of the transposed letter effects was greater in children than in adults, suggesting that children have lexical representations less precisely encoded than adults.

Until now, however, it is not clear whether there is a developmental change in how letter position information is encoded during lexical processing in sentence reading. Thus, a major goal of the present research was to further examine developmental changes on letter position information encoding during sentence reading.

1.2.2. Lexical Selection

Traditional models of word recognition (Interactive Interaction model by McClelland & Rumelhart, 1981; the Dual Route Cascaded model by Coltheart, Rastle, Perry, Langdon & Ziegler, 2001; the Multiple Read-Out model by Grainger & Jacobs, 1996; and the CDP+ model by Perry, Ziegler & Zorzi, 2007) defined orthographic similarity as referring to the concept of orthographic neighbourhood defined by Coltheart *et al.*, (1977). The Orthographic neighbourhood density (N) consists of the number of words that can be created from another word by substituting one single letter, keeping word length and letter order constant. It is found that words with high number of neighbours results in longer identification times or more identification errors than words with low number of neighbours (see e.g., Grainger, 1990; Grainger, O´Regan, Jacobs &

Seguí, 1989). These findings can also vary as a function of the task and the characteristics of the stimuli used such as the relative frequency between the prime and target words (see Andrews, 1997 for a review). This inhibitory effect has been attributed to the fact that similar words (as defined by Coltheart *et al.*, 1977) compete each other to be selected during lexical identification.

Recent models of word recognition (see Davis & Bowers, 2004; 2006; for a review), however, define orthographic similarity in a different way, as a result of all the evidence using transposed letter words (see also Yarkoni, Yap & Balota, 2008). The new concept of orthographic similarity refers to those words that are created from another word by transposing two letters, can be also considered as neighbours (e.g. smile and slime) and are called transposed letter neighbours. Studies using transposed letter words have found similar inhibitory effects as those found with N-neighbours, suggesting that transposed letter neighbours also result in a delayed for lexical identification due to the activation of similar candidates (Acha & Perea, 2008b; Andrews, 1996; Chambers, 1979; Johnson, 2009; Johnson & Dunne, 2012). Alternatively, it has been suggested that this inhibitory effect could be also interpreted as a failure of lexical access due to a target's word misidentification (e.g., Johnson, Staub & Fleri, 2012). In this case, the disruption would not occur during word identification processing but in later stages such as semantic or syntactic integration.

Until now, it is not clear which of the two approaches could explain the evidence found. Thus, a goal of this research was to examine whether transposed letter neighbours influence on lexical or post-lexical processing during sentence reading.

1.3. Eye movements during sentence reading

Studying eye movement behaviour is a powerful tool for understanding linguistic and cognitive processing on a moment-to-moment basis during reading (Liversedge & Findlay, 2000). Recording eye movements allows us to study the pattern of visual inspection and the amount of time readers spend processing words in a natural sentence context (Rayner, 1998, 2009).

Researchers have been interested in when and where a reader moves their eyes in order to read, and in the variables that influence the decisions to move the eyes within the text. Although low-level visuomotor features (e.g., limitations in visual acuity, spaces between words and word length) contribute to *where* the eyes move, substantial empirical evidence has shown that cognitive linguistic processing has a significant influence on *when* the eyes move in reading (Grainger, 2003; Liversedge & Findlay, 2000; Rayner & Liversedge, 2011; Vitu, 2011).

In this chapter, only studies related to the question when the eyes move in reading are described.

1.3.1. Basic Eye Movements

The two basic elements of eye movements are *saccades* and *fixations*. Saccades refer to fast movements of the eyes that take about 20-35 ms to execute. Fixations, periods of time between saccades, when the eyes are quite still, vary between 50 and 600 ms (Rayner, 2009). In reading, the average fixation is between 225 and 250 ms. The acquisition of information is supressed during saccades, and new information is only acquired during fixations (Matin, 1974). Saccade amplitudes in reading vary from one letter space to 15-20 letters spaces but the average saccade amplitude is 7-9 letter spaces. These relatively short movements serve the purpose of bringing new information into foveal vision for detailed processing (Rayner, 1998, 2009). Saccades are necessary due to acuity constraints in the visual system. The retina is composed of three main, symmetric areas; the fovea, the parafovea and the periphery. Although these areas do not have clear boundaries, the fovea is the area with high visual acuity that covers 2° in the centre of vision; the parafovea extends to 5° each side of the fovea, and the periphery is the region beyond the parafovea. Visual acuity is significantly decreased in the parafovea, and drops precipitously in the periphery. Saccades from left to right occur 85-90% of the time when reading alphabetic scripts such as English, while saccades from right to left (regressions) are produced 10-15% of the time.

1.3.2. Key measures and methods

a) Measures of processing time

In reading research, eye movement measures have been used to infer psychological processes associated with reading. In particular, the interest is in where the eyes move and for how long they remain in the different parts of the text. Importantly, there is compelling evidence that the linguistic properties of text have a direct influence on the time it takes to read it (Rayner, 1998, 2009). In this sense, the time taken to process the text is an indicator of the ease with which the processing occurred (Liversedge, Paterson & Pickering, 1998). In this section, key dependent measures will be defined and explained in terms of the underlying cognitive processes that they reflect.

There are two kinds of analysis which involve either the whole sentence (global measures), or analysis of pre-specified regions of the sentence (local measures). Global measures provide information about the general difficulty that the reader experiences with the sentence. These measures generally include mean forward and regressive fixation durations, total number of forward and regressive fixations, and total sentence reading time. In addition, local measures provide information about how the characteristics of specific words or phrases can affect the cognitive processes associated with reading. In this case, the number and location of fixations, and the time spent by the reader in each interest region, are examined (Rayner, 1998, 2009).

Researchers typically discriminate between those measures of eye movements that have been made during first pass reading (the sum of all fixations on a region from first entering the region until first leaving that region) and those that have been made during second pass reading (the sum of all fixations on a region following the initial first pass time). This distinction is important to understand the time course of processing of the different mechanisms implicated in sentence comprehension. Typically, lexical factors such as lexical frequency affect in first pass reading measures while the effect of high-order factors such as syntax, semantics and pragmatics appear during second pass reading (Clifton, Staub & Rayner, 2007; Rayner, Sereno, Morris, Schmauder & Clifton, 1989).

With respect to those measures associated with early stages of processing (first pass reading), first fixation duration is the earliest measure in which one would expect to observe an effect. This is the duration of the first fixation on a region regardless of how many more fixations it subsequently receives. Another early measure is single fixation duration; the time that a word is fixated when it receives only one fixation. Although the best index of processing time depends on the specific experimental manipulation, the two most frequently reported measures are first fixation and gaze durations (Rayner, 1998). Gaze duration is the sum of all consecutive fixations on a word before leaving the word, and is generally considered to reflect lexical identification (Inhoff, 1984). In general, long fixation durations in a specific region will indicate that there are some difficulties in processing this specific region. For example, those words that are infrequent (they appear rarely in texts) will have longer first fixation and gaze durations than frequent words (Rayner, 1986; White, Rayner & Liversedege, 2005a).

With respect to those measures that reflect relatively late text processing effects (second pass reading), a wider variety of measures is used. Four key measures will be considered here: total fixation duration, go past time, refixation probability and regression probability. Total fixation duration is the sum of all fixations on a word (or region) including fixations after regressions. Go past time is the sum of all fixations on a region from first entering the region until moving to the right of the region. Refixation probability is the probability the reader makes additional fixations on the same word following the first fixation, before the eyes leave the word, calculated as a proportion of total number of fixations made on that region. Regression probability is the probability of regressing from the current region to earlier interest regions prior to leaving that region to the right, calculated as a proportion of total number of saccades made on that region. Finally, the number of regressive saccades a reader makes to a region is often reported as an indicator of the difficulty the reader experienced in text comprehension. However, there is some controversy with this measure because it does not take into account the time that the reader spends in earlier portions of the sentence after making these regressive saccades (Liversedge *et al.*, 1998; Rayner, 1998; Rayner & Sereno, 1994). There are three possible eye movement patterns once the reader experiences some difficulties with a word or in a region: (1) they can spend time looking at the relevant section until the difficulty is resolved; (2) they can make a regressive saccade to re-read and re-appraise earlier portions of the text; or, (3) they can make a forward saccade to the next word or region in which additional information may help to solve the difficulty (see Liversedge *et al.*, 1998 for further discussion). Thus, it is important to select the proper eye movement measure depending on the aim of the experiment and the characteristic of the sentences to be able to observe (or not) the effects.

In summary, all these eye movement measures reflect linguistic and cognitive processing on a moment to moment basis during sentence reading. Typically, lexical factors have an effect on early measures while sentences comprehension factors have an effect on later measures.

b) Methods

Evidence concerning parafoveal processing (see Section 1.2.3) has shown that the reader does not just process information from the currently fixated word but s/he is able to process two or three words in a single fixation (see Schotter, Angele & Rayner, 2012 for a review). Although different techniques have been used within eye movement research to study the amount of information that the reader can obtain during each fixation, most of these techniques used in the 60s and 70s (Bouma, 1973; Poulton, 1962; Spearling, 1960; Taylor, 1965) had some limitations, mainly because they were not originally designed to investigate reading, or they were markedly different from, or could disrupt, natural reading processes (see Rayner, 1975; 1986, for a detailed discussion).

Here, the focus will mainly be on the techniques based on gaze-contingent change paradigms used in reading by McConkie and Rayner (1975; Rayner, 1975; Rayner & Bertera, 1979). These techniques permit the study of eye movement patterns while reading. In the following section, data obtained from these techniques will be discussed.

In each of these paradigms, there is a key, shared feature -the display on the reader´s computer screen changes contingent on eye fixation location. In one paradigm, a *moving window* is used, whereby the visible area (window) of text changes contingent on the reader's normal eye movements. In this case, foveal information (information located at the point where the reader is currently fixating) is presented normally while parafoveal and peripheral information (the text outside the window) is disrupted (altered or masked). The size of the window around the point of fixation is manipulated in order to study the amount of information which can be processed in a fixation. When the pattern of eye movements and reading speed are similar to the control condition (where the full line of text is available), this window size indicates the size of the effective visual field in reading (termed the perceptual span).

Another gaze-contingent paradigm is the *moving mask,* a reverse technique in comparison to the moving window, whereby foveal vision is masked, thus allowing only parafoveal visual input to be accessed by the reader (Rayner & Bertera, 1979; Rayner, Inhoff, Morrison, Slowiaczek & Bertera, 1981). Similar to the moving window technique, the size of the mask can be also varied to study its interference with reading. Comparing reading performance when the parafovea is masked with that when the fovea is masked gives us information about the type of information that is obtained. For example, semantic information is obtained in the fovea while partial orthographic information is obtained from the parafovea (Rayner & Bertera, 1979).

Finally, the *boundary paradigm* is used to examine which specific characteristics of a particular word are pre-processed parafoveally before the word is fixated. In this paradigm, an invisible boundary is inserted into the text, and prior to the eyes crossing this boundary the target word is replaced with a parafoveal preview (e.g., an orthographically or phonologically similar word or a nonword). This preview is replaced by the target word when the reader´s eyes make a saccadic movement which crosses the boundary. The advantage of this paradigm is that during a saccade, the visual uptake of information is suppressed, which means that the reader is typically not aware of the change (McConkie & Rayner, 1975; Rayner, 1975). Thus, comparing fixation times on the target word as a function of the nature of the preview string allows us to know what characteristics of the target word are extracted from the parafovea and facilitates word identification.

1.3.3. Parafoveal Pre-Processing

Research on parafoveal processing has shown that readers obtain facilitation from the word to the right of the fixated word (Rayner, 1998, 2009; Schotter, Angele & Rayner, 2012). This suggests that some linguistic information is extracted from the parafovea before the word is directly fixated, in order to facilitate the identification of that word when it is fixated. To know what kind of information is extracted from the parafovea, researchers have used gaze-contingent paradigms (see Section 1.3.2). Here, evidence concerning parafoveal pre-processing during reading will be described.

1.3.3.1. Perceptual Span

Research using the moving window paradigm (see Section 1.3.2.) has investigated the size of the area from which useful information can be obtained during a fixation. In adults, the perceptual span extends over an asymmetrical area from 3-4 characters spaces to the left of the fixated word to 14-15 character spaces to the right of fixation in alphabetic languages (McConkie & Rayner, 1975; Rayner, 1986).

Different kinds of information can be extracted from different areas within the perceptual span. Word identification occurs in the area closest to fixation, generally, between 3-4 letters to the left and 6-7 letters to the right of fixation but the boundaries are not fixed. In parafoveal vision (approx. 6-15 letters to the right of fixation), readers can obtain partial orthographic and phonological information about the upcoming word that has not been yet identified. In the periphery (more than 15 letters character position from the fovea), low spatial frequency features such as the spaces between words are processed

(McConkie & Rayner, 1975; Rayner, 1975; Rayner & Bertera, 1979; Rayner *et al.*, 1981; Rayner, Fisher & Pollatsek, 1998; Rayner, Well & Pollatsek, 1982).

A large body of evidence has shown that both the asymmetry and size of the perceptual span vary as a function of the direction of reading in different languages. For instance, in Arabic and Hebrew, which is read from right to left, the effective area of vision is asymmetrical with a greater span to the left (Jordan, Almabruk, Gadalla, McGowan, White, Abedipour & Paterson, 2014; Pollatsek, Bolozky, Well & Rayner, 1981). In addition, in Chinese where the orthographic information is more densely packed, the perceptual span is smaller than in English: 1 character to the left and up to 3 characters to the right of fixation (Inhoff & Liu, 1998). Furthermore,. These findings are important because they suggest that the perceptual span is under cognitive control. This does not mean that is a conscious control, rather it means that the perceptual span varies depending on cognitive demands. Additionally, difficulty of the text (Henderson & Ferreira, 1990; Hyönä, 1995; Inhoff & Liu, 1998; Ikeda & Sada, 1978; Osaka, 1993; Rayner, 1986), reading ability (Ashby, Yang, Evans & Rayner, 2012; Häikiö *et al.*, 2009; Rayner, Slattery & Bélanger, 2010; Veldre & Andrews, 2014), and age (Apel, Anderson & Ferreira, 2012; Häikiö *et al.*, 2009; Jordan, McGowan & Paterson, 2013; Rayner, 1986; Rayner, Castelhano & Yang, 2009) can also make the size of the perceptual span vary (Rayner, 1986; Hyönä, 1995; Henderson & Ferreira, 1990). For example, beginning child readers have a smaller perceptual span than older child readers (Häikiö *et al.*, 2009; Rayner, 1986). suggesting that attentional and cognitive processes are the engine that determines when and where the eyes move to the next word.

All these findings support the idea that attention and on-going processing constraints, and not only visual acuity, determine how much useful information is obtained during a fixation in reading (Rayner, 2009).

1.3.3.2. Information extracted from the parafovea

As mentioned before, readers do not only process information from the currently fixated word but they also pre-process information from the word to the right of the fixated word. Studying what kind of information is extracted from the parafovea allows us to know the variables that facilitate word identification when the word is directly fixated (see Schotter *et al.*, 2012 for a review).

A large body of evidence has found that adults extract information from the parafovea regarding word space and word length to narrow down possible number of lexical candidates (Inhoff *et al.*, 1998; Inhoff, Eiter, Radach & Juhasz, 2003; Juhasz, White, Liversedge & Rayner, 2008; White, Rayner & Liversedge, 2005b; Johnson *et al.*, 2007; White *et al.*, 2008) as well as partial orthographic and phonological information from the parafovea, facilitating lexical processing once the word is fixated (e.g., Briihl & Inhoff, 1995; Johnson *et al*., 2007; Henderson, Dixon, Petersen, Twilley & Ferreira, 1995; Lima & Inhoff, 1985; Miellet & Sparrow, 2004; Perea & Pollatsek, 1998; Pollatsek, Perea & Binder, 1999; Pollatsek, Lesch, Morris & Rayner, 1992; Rayner, Pollatsek & Binder, 1998; Rayner, Sereno, Lesch & Pollatsek, 1995; Rayner & Pollatsek, 1989; Sereno & Rayner, 1992, 2000; Williams, Perea, Pollatsek & Rayner, 2006; Yates, Friend & Ploetz, 2008). Few studies, however, have explored developmental changes on parafoveal pre-processing. This is mainly due to technical difficulties in tracking children's eyes using less sophisticated hardware in the past. Now the availability of more advanced eye trackers allows for recording children's eye movements with relative ease and improved accuracy. These studies have shown that despite their reduced perceptual span, children are able to pre-process information from the parafovea (Häikiö *et al.*, 2010; Tiffin-Richards & Schroeder, 2015). Until now, there were no studies investigating parafoveal processing in

English children. Thus, a goal of the present research was to investigate parafoveal pre-processing in English child readers (see Chapter 3).

1.3.3.3. Parafoveal on Foveal effects

One of the most important questions is how attention is allocated for lexical processing during sentence reading. There are two approaches. One approach assumes that attention is allocated serially such that only one word can be fully identified at a time. The second approach assumes that attention is lexically distributed over space such that multiple words can potentially be fully identified at the same time. The two most developed computational models of reading that keep open the debate about how attention is allocated during reading are the E-Z Reader (serial) and SWIFT model (parallel) (See Section 1.3.5. for a description of the models)

Parafoveal on Foveal (PoF) effects are very important for this debate because they could be the evidence that supports the approach of parallel attention for lexical processing. If the lexical properties (phonology, orthography or semantics that are available only when a word is identified) of the parafoveal word influence the processing time on the foveal word, then this effect will be considered as a PoF effect and would suggest that the parafoveal word has been fully identified before the word has been fixated. This would indicate that during a fixation, the reader was able to fully identify the foveal and parafoveal words at the same time, supporting the claim that attention is allocated in parallel for word identification.

Similarly, if partial orthographic, phonological or semantics information of the parafoveal words influences processing time on the foveal word, it is also considered a PoF effect. In this case, however, this effect suggests that the reader is pre-processing partial information to facilitate word identification once the word is fixated. This would indicate that only the foveal word has been fully identified during one fixation, and some partial visual or linguistic information of the following word has been pre-processed at the same time. This would support the claim that attention is allocated serially for word identification.

Although in both cases, the effects are considered PoF effects, only in the first case would be evidence of parallel lexical identification (as per in SWIFT model).

The PoF effects reported are mainly from studies that have used corpus study methodology, in which a large amount of data is collected and correlational analyses are carried out (for example, Kliegl, Nuthmann & Engbert, 2006). However, in controlled reading experiments containing orthogonal manipulations, PoF effects occur rarely, and are typically attributed to factors such as inaccurate eye tracker calibration, mislocated fixations, and binocular disparity (see Drieghe, Rayner & Pollatsek, 2008; also for a review Drieghe, 2011). Furthermore, the size of PoF effects is very small, and they only appear when short foveal words are fixated (White, 2008) and, generally, these effects tend to disappear when analysing the fixations falling on final characters of the pre-target word, being explained by mislocated fixations instead of parallel lexical processing (Inhoff, Starr & Shindler, 2000; Rayner, Warren, Juhasz & Liversedge, 2004; Drieghe *et al.*, 2008). For example, Rayner *et al.* (2004) studied the role of plausibility on eye movement behaviour and the time course of the plausibility effect during a sentence reading task. They constructed three different types of sentences: a plausible control (*John used a knife to chop the large carrots for dinner*), an implausible version (*John used an axe to chop the large carrots for dinner)* and an anomalous version (*John used a pump to inflate the large carrots for dinner).* This anomalous version reflects extremely improbable real world events. They found PoF effects, such that they found increased fixation durations on the pre-target word (large) in the anomalous condition, but only when the analysis was based on the final three characters of the pre-target word. This result suggests that the PoF effect found in this experiment can be explained by mislocated fixations instead of parallel lexical processing.

Similarly, Drieghe *et al.* (2008) presented five-letter pre-target words which were high (*children*) or low frequency (*tenor*) and followed by the target word with two previews: correctly (*performing*) or incorrectly spelled (*pxvforming*). They expected to obtain a PoF effect when the target preview was orthographically illegal, and/or with high frequency pre-target words (because this should allow more processing resources to be allocated to the next word in the sentence, e.g., the preview string) and the effects should not be restricted by the amplitude of the previous saccade. However, although they found a PoF in the expected direction, this was solely driven by particular trials where the location of the fixation was on the very last letter of the pre-target word. This study is one of the strongest evidence to date supporting the argument that PoF effects are mainly due to mislocated fixations.

The most recent evidence comes from the study by Angele *et al.* (2015). In this study, they combined a corpus analysis approach with an experimental manipulation, using a moving mask technique (Rayner & Bertera, 1979). They presented a mask for a) the parafoveal word (n+1), b) the second parafoveal word to the right of the fixated word (n+2), c) for both (n+1 and n+2), d) no mask for neither words. Although they found increased fixation times when either or both parafoveal words were not predictable or of low frequency (and similar to findings from corpus studies), they found these effects even when the parafoveal word was masked, suggesting that these effects could be caused by factors that are unrelated to lexical parafoveal preprocessing.

As it was mentioned before, evidence for PoF effects is a key issue with respect to the debate concerning whether multiple words are processed in parallel or serially. For this reason, it is important to assure that the cause of a PoF effect is not due to inaccurate eye tracker calibration, mislocated fixations, or binocular disparity in a controlling reading experiment. To date, there is not conclusive evidence to support either perspective, thus the current debate about serial or parallel lexical processing remains open.

1.3.3.4. Word skipping

Although word skipping effects are not relevant for this thesis, I will briefly describe these effects due to their relevance on parafoveal processing for the debate about whether words are processed in parallel or serially.

One third of all words are initially skipped during reading (Rayner, 1998, 2009). Researchers have attributed the cause of skipping to the fact that the skipped word has been fully identified, before it is fixated and the system takes the decision to skip that word and fixated the following word. A consequence of the skipping, there is an increase in fixation time on the fixated word, prior to the following word being skipped, similar to PoF effects mentioned before. This would suggest that multiple words can be fully identified in parallel.

There are three main factors that influence skipping rate: word length, word predictability and lexical frequency. Rayner (1979) found that short parafoveal words (fewer than three letters) are more likely to be identified and skipped than long parafoveal words (more than 7 letters); these long parafoveal words had a higher probability of being fixated and refixated.

In addition to word length, short, predictable and high frequency words are more likely to be skipped than long, unpredictable and low frequency words (Brysbaert, Drieghe & Vitu, 2005; Brysbaert & Vitu, 1998; Rayner, Sereno & Raney, 1996; Rayner, Slattery, Drieghe & Liversedge, 2011). For example, Rayner *et al.* (2011) examined whether predictability affected skipping words of different lengths, as well as the effect of word predictability on fixation times on the target word when it was not skipped. The materials used in each trial consisted of two sentences: the first sentence established the context which did or did not predict the second sentence, while the second sentence was the same in both conditions (e.g. predictable: *Gary had become a compulsive liar. He just couldn't seem to tell the truth about anything*; unpredictable: *Gary had some mental health issues. He just couldn't seem to tell the truth about anything)*. Target words were short (4–6 letters), medium (7–9 letters) or long (10–12 letters) (e.g. *truth/airport/earthquake*). The results showed that word skipping was influenced independently by both word length and predictability: short and predictable words were more likely to be skipped than long and unpredictable words.

Taking these studies together, word length, word predictability and lexical frequency are the variables that influence the probability of skipping words, suggesting that parafoveal word (if it is short, frequent and predictable) can be fully identified before it is directly fixated.

1.3.4. Foveal Processing

With respect to the question of how long the eyes fixate on a word before moving to another word in the sentence, it has been shown that visual information is encoded during the first 50 ms of the fixation, but that other processes (e.g., programming the following saccade, feature integration at a higher level, parafoveal pre-processing and linguistic processing of the current word) require more time (up to about 200-250 ms) (Liversedge, Rayner, White, Vergilino-Perez, Findlay & Kentridge, 2004; Rayner *et al.*, 1981; Rayner, Liversedge, White & Vergilino-Perez, 2003). Although there are many factors that affect when the eyes move to the next word (pre-lexical, lexical and post-lexical factors, see Rayner, 2009 for a review), here only the pre-lexical and lexical factors that affect when they eyes move to the next word will be described due to their relevance for the present research.

1.3.4.1. Pre-lexical factors

In the next section I will focus on orthographic and phonological information influences the foveal processing of words because these two factors are of primary relevance to this thesis.

Some eye movement studies have focused on the role that encoding of letter information (identity and position) plays in reading. Word identification requires knowing both the identity and the position of each letter in the sequence to be able to distinguish between words such as CLAM and CALM (Johnson, 2009). Furthermore, the letters of a word can be grouped into larger units such as bigrams (a pair of adjacent or non-adjacent letters) or trigrams (three adjacent letters) and these could play a role in word identification.

With respect to the role of letters, Lee, Rayner and Pollatsek (2001, 2002) studied the time course of processing for consonants and vowels in word reading using a fast priming task (where the visual onset of specific letters was delayed at the beginning of a fixation on the target word). They found that consonants were processed faster than vowels in the early stages of foveal processing (e.g., with a 30 ms delay), but no differences between them were found for a delay of 60 ms. This supports the argument of a temporal distinction between consonants and vowels in lexical identification during reading: consonants are more informative in early stages of lexical processing while vowels are more important in later stage of lexical processing (e.g., Berent & Perfetti, 1995).

Transposed letter studies have examined the cost to processing for words in which the positions of two letters are swapped (transposed letters nonwords) compared to when words are presented normally. Evidence has shown that there is a cost to processing words with transposed letters compared to when words are presented correctly spelled (Rayner *et al.*, 2006), and word-initial transposed letters caused more interference than word-final transposed letters (White *et al.*, 2008). These studies suggest that although there is a cost to processing transposed letter nonwords, it is less for internal letter locations than for initial letters, indicating that letter position information for initial letters is very important, mainly due to their important role as lexical access units, because the phonological code provided by the initial letters allows the reader to initiate lexical access (see Chapters 3 & 4).

Concerning sublexical units such as bigrams, White and Liversedge (2004) studied the type of information that can affect the time of word processing. They found that correctly spelled words (*agricultural*) had shorter fixation times than the misspelled words (*acricultural, aoricultural, akricultural, ngricultural*). Furthermore, illegal misspelled words (*ngricultural*) had longer fixation times than high frequency misspelled words (*acricultural*) for both first fixation and gaze duration, suggesting that the very irregular misspellings were more difficult to process than the correctly spelled words. All these studies show that partial orthographic information is activated early, influencing fixation times on the word during lexical identification in reading.

Another important question is whether readers activate phonological codes at an early, pre-lexical stage during lexical processing (Sereno & Rayner, 1992; Rayner, Pollatsek & Binder, 1998; Rayner *et al.*, 1995) or late, after lexical access (Daneman & Reingold, 1993; Daneman Reingold & Davidson, 1995). Although Daneman *et al.* suggested that phonological codes were activated late, after lexical access, Rayner *et al.* (1998) argued for pre-lexical phonological processing. They examined reading of homophone pairs embedded in sentences, and showed that phonological encoding occurs early in the processing of a word, specifically when both members of the pair were orthographically similar (break-brake or bear-bare). They suggested that the main differences between their study and the study by Daneman *et al.* were that in the latter, they did not included a spelling control condition and that they focused the analyses on gaze duration and regressions back, late measures of word processing. They could not, therefore, observe early activation of phonology (see the discussion by Rayner *et al.*, and convergent evidence in Sereno & Rayner, 1992; Rayner *et al.*, 1995). To sum up, there is a body of evidence supporting the view that partial orthographic and phonological codes are activated early during lexical identification in reading, influencing fixation times on the words.

1.3.4.2. Lexical factors

Lexical processing is one of the most important processes involved in sentence comprehension. Although, there are many lexical factors that influence the decision of when the eyes move to the next word (see Rayner, 2009 for a review), here I will only focus on word length, word frequency, age of acquisition and word predictability because they are the most well documented effects. Each of these will now be briefly discussed, in turn.

With respect to word length, research has found that long words (more than 7 letters) attract longer reading times than short words (fewer than 4 letters) (e.g., Hyöna, 2011; Hyöna & Olson, 1995; Rayner 2009). There are two reasons for the word length effect. First, the final letters in a long word are not as visible as in a short word, so readers may need to make refixations in order to identify the word (Hyönä, 2011). Second, when keeping constant the spatial extent, longer reading times are shown when the words have more letters due to visual crowding (McDonald, 2006).

Concerning word frequency, when word length is controlled, many studies have shown that frequent words receive shorter fixation durations than infrequent words (e.g., Henderson & Ferreira, 1990; Rayner, 1986; Rayner *et al.*, 2003; Rayner, Ashby, Pollatsek & Reichle, 2004; White *et al.,* 2005a). The more exposed a reader is to a word, the less time they need to identify it. It is generally argued that this occurs because the threshold for identification, or the baseline resting activation rate for a word is reduced with each successive exposure (e.g., Rayner & Duffy, 1986).

Another lexical variable that has an effect on eye fixations times is Age of Acquisition (AoA, the age at which those words are typically learned), early AoA words attract shorter fixation times than late AoA words (Juhasz & Rayner, 2003, 2006). It has been argued that lexical representations are stored as a function of a chronological dimension such that early acquired words are stored in deeper levels of cortical representation, making them more accessible for word identification than words learned later in life (e.g., Carroll & White, 1973).

With respect to word predictability, predictable words within a sentence received shorter fixations times than unpredictable words (Drieghe *et al.*, 2005; Kliegl, Grabner, Rolfs & Engbert, 2004). This is because the previous context constrains the identity of the following word (predictable), facilitating word identification and resulting in shorter fixation times than unpredictable words (less constraint by the previous context).

Here I will describe the evidence regarding the factors that influence foveal processing in children. The relevance of studying children's reading is based on the lack of information about the process of reading development to get to the skilled reading. As I described previously, we know a lot about skilled reading, but we do not have much evidence about how children process language and how it develops over the lifetime.

Proportionately, the number of studies investigating reading in children is now growing faster than the number of studies investigating adults' reading. Only recently, has recording children's eye movements become relatively easy and accurate thanks to the availability of the more advanced eye trackers.

The pattern of eye movements found for children differs from the pattern described in adults previously. Children are known to make more first pass fixations, shorter progressive saccade amplitudes, longer fixations duration and longer total reading times than adults (e.g., Blythe, 2014; Blythe *et al.*, 2006, 2009, 2011; Häikiö *et al.*, 2009, 2010; Huestegge *et al.*, 2009; Joseph *et al.*, 2009; Mancheva *et al.*, 2015; McConkie *et al.*, 1991; Rayner, 1986; Reichle *et al.*, 2013; Tiffin-Richards & Schroeder, 2015; Zang, Liang, Bai, Yan & Liversedge, 2012). Until now, these differences have been attributed to the fact that lexical processing is slower in children compared to adults. This has been supported by evidence from simulations using the E-Z Reader model (Mancheva *et al.*, 2015; Reichle *et al.*, 2013).

Concerning the factors that influence foveal processing in children's reading, I will focus here on word length, lexical frequency and semantic effects because these are the only factors that have been studied until now.

Research has shown that developmental changes associated with visual processing can influence linguistic processing during sentence reading. Regarding word length effects, children showed larger word length effects than adults in gaze duration, and were more likely to refixate a word during first pass, suggesting that children needed a second visual sample on longer words in order to read as effectively as adults (Blythe, Häikiö, Bertam, Liversedge & Hyönä, 2011; Joseph, Liversedge, Blythe, White & Rayner, 2009). Regarding lexical frequency effects, Blythe, Liversedge, Joseph, White and Rayner (2009) found word frequency effects in both children and adults, in both normal and disappearing text reading conditions, when the time of disappearing text was manipulated (40, 60, 80 and 120 ms). In adults, reading times were not affected when the text disappeared after 60 ms; children, by comparison, found it more difficult to read the disappearing text than normally presented text. Interestingly, within the briefest presentation duration (40 ms), all the groups showed word frequency effects in single, first fixation and gaze durations. This lexical frequency effect found in children demonstrates that linguistic processing of the text affects children´s fixation duration in the same manner as in adults relating to when the eyes move to the next word. Finally, Joseph *et al.*, (2008) examined whether the time course of semantic processing was similar in children to adults. They found that both adults and children showed longer reading times for anomalous rather than control sentences, indicating that the processing time of thematic relations is similar in both adults and children. Children were delayed, however, when they read implausible sentences. Joseph *et al.* concluded that although children and adults were similar in basic thematic processing during comprehension, children were less efficient to integrate pragmatic knowledge into the discourse representation.

In summary, both pre-lexical factors such (as partial orthographic and phonological information) and lexical factors (such as word length and lexical frequency) affect the duration of fixations on a word in adults. This evidence supports the theoretical stance that the decision of when they eyes move to the next word is based on linguistic and cognitive processing during sentence reading. It is not clear yet, which pre-lexical and lexical factors can influence lexical processing in children during sentence reading. Thus, a goal of this research is to further explore the influence of orthographic information on both parafoveal and foveal processing in sentence reading by children.

1.3.5. Eye movement models of reading

Although there are a number of models of reading, the two most developed computational models of reading, which are used to accommodate the empirical evidence discussed in previous sections, will be discussed. In particular, the focus will be the E-Z Reader (serial processing) and SWIFT (parallel processing) models because they keep open the debate about how the attention is allocated during reading.

1.3.5.1. Serial Attention models (stochastic models)

The main assumption of serial attention models is that attention is allocated sequentially to support the lexical processing of only one word at a time, and that lexical processing normally causes the eyes move from one word to the next (Reichle, 2006, 2011). The most developed serial model is the E-Z Reader (Reichle, Pollatsek, Fisher & Rayner, 1998) which is based on earlier models such as the Reader model by Just and Carpenter (1980) and EMMA model by Salvucci (2001). The E-Z Reader model can accommodate most empirical findings in eye movement research in reading (Reichle, Rayner & Pollatsek, 1999, 2003; Reichle, Warren & McConnel, 2009). This model is composed of the three core components- saccadic programming, lexical processing, and higher language processing. Here, the focus will be on the first two components as they are directly relevant to this thesis.

In E-Z Reader, saccadic programming is composed of two stages which can be completed in parallel: a *labile* stage (in which a saccade can be cancelled) and *non-labile* stage (in which a saccade cannot be cancelled). Furthermore, the labile stage is divided into another two sub-stages: the *preparatory* stage in which the location to which the outgoing saccade will be targeted is identified (usually to the centre of the next word); and a *translation* stage where the spatial target is converted into a metric distance.

Lexical processing is performed in two stages: a preliminary stage (L1, where a saccade starts to be programmed in order to move the eyes) in which a familiarity check is made. The time to complete this stage is established as a function of lexical frequency and predictability. The second stage is lexical access (L2), which is the process of activating semantic representations, and this causes attention to shift to the next word. These assumptions are based on those models that proposed a dual process for word recognition: activation-verification models (Paap, Newsome, McDonald & Schvaneveldt, 1982, see also Reichle & Perfetti, 2003)

1.3.5.2. Parallel Attention Gradient models (dynamic models)

The most advanced and representative parallel processing model of reading is the Saccade Generation with Inhibition by Foveal Target (SWIFT) model by Engbert et al. (SWIFT-I, Engbert, Longtin & Kliegl, 2002; SWIFT-II, Engbert, Nuthmann, Ritchter & Kliegl, 2005). In this model, there is a spatially distributed lexical processing over the fixated word.

In the first version of the SWIFT model, it was proposed that up to four words could be processed in parallel through a mechanism by which processing the fixated word is the highest point, and it decreases symmetrically to both sides of the point of fixation. In SWIFT-II, the authors describe the model as following seven principles. The first principle is called *spatially distributed processing of an activation field*, where lexical competition is generated by varying levels of activation per words and multiple words can be activated at the same time (Erlhagen & Schöner, 2002). The second principle proposes *separate pathways for saccade timing and saccade target selection* based on neurophysiological evidence which has shown that the when and where pathways are independent (Van Gisbergen, Gielen, Cox, Bruijins & Kleine, 1981; see also the functional model proposed by Findlay & Walker, 1999). The third principle says that saccade generation timing is planned independently and randomly. This is influenced by a foveal inhibition process which means that the majority of saccades will move the eyes to a new word in the sentence with delayed time for difficult words. The fourth principle divides saccade programming into labile and non-labile stages (Becker & Jürgens, 1979) to distinguish between the time over in which the saccade is planned (and can be cancelled) and the time over which the saccade is executed (and cannot be cancelled). The fifth principle differentiates the saccadic amplitude errors into two types: systematic (dependent on launch site distance), and random (in fixation position). The sixth principle proposes a mechanism to correct mislocated fixations (Drieghe *et al.*, 2008; Rayner *et al.*, 2008). This mechanism assumes that a new saccade is generated immediately after the execution of the first one. Thus, when the eyes land on unintended words, the target of the new saccade will be determined at the end of the labile stage of the previous saccade, resulting in systematic shifts in within-word landing position distributions as a function of launch site distance. Finally, the seventh principle states that saccade latency is influenced by the amplitude of the intended saccade, which is computed at the end of the labile stage according to basic oculomotor research (e.g., Wyman & Steinman, 1973).

Importantly, serial and parallel processing models agree on the assumption of parallel saccade programing and lexical processing. The controversial point between them is whether multiple words are lexically processed at the same time (e.g., SWIFT) or only one word at a time (e.g., EZ-Reader). Reichle, Liversedge, Rayner and Pollatsek (2009) argued that one of the main reasons why multiple words cannot be processed simultaneously during reading comes from evidence regarding word identification models, where word identification occurs through a lexical competition mechanism which generates a single output (“the winner takes all” principle). Furthermore, the orthographic activation of two words at the same time provokes noise in the recognition process, which would lead to an increase in word identification time and/or could produce a failure in word selection (see Reichle, Liversedge et al., 2009, for a detailed discussion).

As mentioned before, the E-Z Reader and SWIFT models are the most developed computational models that can explain most of evidence found in reading, including children's reading (Reichle *et al.*, 2012; Mancheva *et al.*, 2015). The current debate about serial or parallel lexical processing is still open.

One important issue that needs to be raised in the present research is that models of eye movement control are mainly designed to account for eye movement control and not for word recognition. This just reflects the current position in understanding the processes underlying reading. Researchers must develop accounts of lexical processing that can be realistically incorporated into models of eye movement control. For example, these accounts should explain how lexical processing is distributed across successive fixations, employing both parafoveal and foveal information for word identification during reading. Thus, the present research extends the literature of letter position encoding during lexical processing to sentence reading by examining the pattern of fixations and saccades that readers make.

1.4. Overview of studies in the present thesis

All the studies that form this thesis represent an attempt to systematically investigate developmental changes in how letter position information is encoded during lexical processing in sentence reading. This research will extend our knowledge about children's reading in comparison to adults' reading, specifically how lexical processing ocurrs and possible developmental changes associated with children's reading ability.

Each of the empirical chapters that follows is formatted as an individual journal article or manuscript that has either been accepted (Chapters 2 and 3) or submitted (Chapter 4) for publication in a peer-reviewed journal.

Chapter 2 (Pagán, Paterson, Blythe & Liversedge, 2015) investigates whether prior exposure to a word's transposed letter neighbour earlier in the same sentence can disrupt processing of that word in skilled adults. Participants in this experiment had many years of experience, knowledge of words and a great number of high quality lexical representations. Thus, this experiment establishes the influence of letter position encoding on the time course of the processes that occur during both lexical and post-lexical processing in sentence reading by skilled readers.

Chapter 3 (Pagán, Blythe & Liversedge, 2015) examines whether children extract letter position information independently from letter identity information from the parafovea as adults do. In this experiment, an invisible boundary paradigm (Rayner, 1975) was used as both adults and children read sentences. This experiment demonstrated that children do pre-process orthographic information from the parafovea, and encode letter position information similarly to adults.

Chapter 4 (Pagán, Blythe & Liversedge, submitted) explores whether children's reading ability influences how letter position information is encoded during lexical processing in sentence reading. Here, we did not use the boundary paradigm for a very specific reason. The interest of this experiment was in how reading ability modulated orthographic encoding. An important concern was that less skilled child readers would, potentially, exhibit reduced and less efficient parafoveal processing, given their reduced perceptual span (Häikiö *et al.*, 2009). For this reason, a stronger manipulation of orthographic encoding was used, that it, one that involves less subtle manipulations of the orthographic information that a reader has available to process. In this experiment, adults, skilled and less skilled child readers read sentences with words that included words containing two letters transposed that remained on the screen unchanged throughout the entire trial. This experiment demonstrates a developmental change in letter position encoding as a function of the reader's ability reflected by the quality of their lexical representations.

Finally, Chapter 5 summarizes the important findings from this research and discusses the implications of this work.

The present research extends the literature on letter position encoding from isolated word paradigms to eye movements in normal reading in two ways. First, by examining the influence of letter position encoding on the time course of lexical and post-lexical processing in skilled adults. Second, by examining such processing in children, its relation with reading ability, and so, the lexical quality hypothesis, thereby establishing a possible explanation for the differences found in letter position encoding between adults and children.

Chapter 2: An Inhibitory Influence of Transposed Letter Neighbors on Eye Movements during Reading

The contents of this chapter are a minor revision of Pagán, Paterson, Blythe & Liversedge (2015) accepted in *Psychonomic Bulletin & Review, 1-7*[1].

2.1. Abstract

Previous research shows that prior exposure to a word's substitution-neighbor earlier in the same sentence can disrupt processing of that word, indicating that inter-word lexical priming occurs naturally during reading, due to competition between lexical candidates during word identification. The present research extended these findings by investigating effects of prior exposure to a word's transposed-letter neighbor (TLN) earlier in a sentence. TLNs are constituted from the same letters but in a different order. The findings revealed an inhibitory TLN effect, with longer total reading times for target-words, and increased regressions to prime and target-words, when the target followed a TLN rather than a control word. These findings indicate that prior exposure to a TLN can disrupt word identification during reading. We suggest that this is caused by failure of word identification due to the initial misidentification of the target-word (potentially as its TLN) triggering post-lexical checking.

[1] Experimental design, data collection, analysis and write-up were completed by Ascensión Pagán under the supervision of Kevin Paterson, Hazel Blythe and Simon Liversedge.

2.2. Introduction

Isolated-word recognition studies show that prior exposure to an orthographically similar word affects how rapidly a word is recognized (Andrews, 1997). Recent research has focused on the influence of substitution-neighbors (words created from another word by the substitution of one-letter, preserving word-length and letter-order), showing that prior presentation of a substitution-neighbor as a prime can inhibit subsequent target-word recognition, contingent on prime duration and the relative frequencies of prime- and target-words (Coltheart, Davelaar, Jonasson & Besner, 1977). For instance, when a masked prime is presented for short durations (e.g., 60ms), larger inhibitory effects are observed when the prime is of higher frequency than the target (Davis & Lupker, 2006). Competitive network models of word recognition (Davis, 2010; McClelland & Rumelhart, 1981) attribute this effect to the higher-frequency neighbor prime giving a lexical competitor a "head-start" in processing thereby interfering with target-word recognition. By comparison, when an unmasked prime is presented for longer durations (e.g., 250ms), inhibitory effects are larger when the prime is of lower-frequency (Segui & Grainger, 1990). In this case, conscious prime identification inhibits higher-frequency lexical competitors, impeding recognition of the higher-frequency target-word.

Such findings are informative about the nature and time-course of orthographic influences on word recognition and are fundamental to computational models of word recognition. But how these factors influence the lexical identification process during text reading is yet to be fully-established. Several studies show that a word's lexical neighborhood can affect lexical identification during reading (Perea & Pollatsek, 1998; Slattery, 2009). For example, Perea and Pollatsek (1998) found that words with a higher-frequency substitution-neighbor receive longer total reading times than control-words, and so reveal that neighborhood effects occur naturally during reading. Moreover, other studies show that encountering a word's substitution-neighbor a few words earlier in the sentence can influence fixation times on that word (Carreiras, Perdomo & Meseguer, 2005; Frisson, Koole, Hughes, Olson & Wheeldon, 2014; Paterson, Davis & Liversedge, 2009). For instance, Paterson *et al.* (2009) found that prior exposure to a word's substitution-neighbor (e.g., "blue") rather than a control word (e.g., "town"), in a sentence such as "In the photograph, the blue lights were a blur against the cold night sky", produced longer fixations on the target-word "blur". This inhibitory effect emerged in the first-fixation on the target-word, but was unaffected by the relative frequencies of prime- and target-words, and showed inter-word priming effects occur naturally during reading. Frisson *et al.* (2014) subsequently showed this effect is strongest when the neighbor-word overlaps both orthographically and phonologically with the target. Wang, Tian, Han, Liversedge, and Paterson (2014) also demonstrated more recently an analogous effect in Chinese, in which prior exposure to a Chinese character that differs by one or two character strokes, and phonologically, from a target-character can inhibit character processing.

These findings provide strong evidence for lexical competition during word identification during reading. However, the findings contrast with those from research using a word's substitution-neighbor as a parafoveal preview in the boundary paradigm (Williams, Perea, Pollatsek & Rayner, 2006). Here, when the neighbor appears in place of the target-word before a saccade is made to fixate that word, facilitation rather than inhibition occurs. In this situation, the parafoveal preview activates orthographic features of the word without strongly activating competing lexical entries, and target-word identification is facilitated. The indication, therefore, is that parafoveal preview of a word's neighbor does not initiate lexical competition, but that prior exposure to a word's neighbor earlier in the sentence can interfere with lexical/character identification.

It remains to be determined, however, if other inter-word orthographic relationships affect word identification during normal reading and whether such effects are due to lexical competition. An important example concerns words formed by the transposition of two letters in one word to form another (e.g., "scared" and "sacred" are transposed letter neighbors-TLNs). Such words reveal the role of letter-position (as well as identity) during word processing and, in particular, whether letter-position is encoded strictly or flexibly. Traditional word-recognition models (McClelland & Rumelhart, 1981) assume that letter-identity and position are encoded at the same time, resulting in a strict definition of orthographic similarity (substitution-neighbors). However, evidence from experiments using TL-nonwords shows that TL-nonwords produce greater activation of their base words than letter substitution-nonwords, resulting in a more flexible definition of orthographic similarity (Grainger, 2008). As a consequence, more recent models of letter-position encoding assume that TLN are more orthographically similar than substitution-neighbors, predicting similar or even greater inhibitory effects than those for substitution-neighbors (e.g., Davis & Bowers, 2006).

Evidence from isolated word recognition studies using TLN is scarce and controversial. In some studies, TLN have caused inhibitory effects that occurred in later stages of lexical processing (Andrews, 1996; Chambers, 1979), while in others studies, these stimuli have produced null (Perea, Acha & Fraga, 2008; Castles, Davis & Forster, 2003; Duñabeitia, Perea & Carreiras, 2009; Duñabeitia, Molinaro, Laka, Estévez & Carreiras, 2009) or facilitatory effects (see Andrews, 1996; Castles, Davis, Cavalot & Forster, 2007). The inhibitory TLN effects are sometimes interpreted not as lexical competition but failure of lexical access due to a target-word's misidentification (e.g., Johnson, Staub & Fleri, 2012). Inhibitory TLN effects in later eye movement measures are also observed when words with TLN are embedded in sentences (Acha & Perea, 2008; Johnson, 2009), while studies using the boundary paradigm (Johnson & Dunne, 2012) produced facilitatory effects similar to those reported by Williams et al. (2009) for substitution-neighbors. It remains to be shown, however, whether TLN effects that are observed between words that are encountered naturally during reading, without manipulation of parafoveal preview, are inhibitory or facilitatory.

Accordingly, the present experiment examined the influence of prior exposure of a TLN on the processing of words during reading. As in the substitution neighbor's study by Paterson *et al.* (2009), the TLN was encountered normally a few words earlier in the same sentence. If prior exposure to a TLN is facilitatory due to prior identification of the TLN pre-activating low-level orthographic information shared with the target-word, target-word identification will be facilitated, resulting in shorter fixations on that word. In contrast, if prior exposure to the TLN is inhibitory, this will slow target-word identification, producing longer fixation times on the target-word. In this case, the time course of the inhibitory effects will be critical to distinguish between two possible explanations. If effects are observed early, for example, affecting first pass measures on the target word, this would suggest that prior exposure to a TLN produces lexical competition between the TLN and target words. However, if the effect occurs later during processing, for example in those measures that affect re-reading behavior, this would suggest that the TLN caused the target-word to be initially misidentified, resulting in post-lexical checking.

2.3. Method

2.3.1.Participants

Twenty-eight undergraduate students (*M*=22 years) from the University of Southampton participated for course-credits. All participants were native English speakers, had normal or corrected vision, and showed no evidence of reading difficulties, as assessed using the Wechsler Individual Achievement Test-II (Wechsler, 2005).

2.3.2. Materials and Design

Twenty-nine sets of words between 4- and 6-letters long (*M*=5 letters) were selected. Each set comprised a target-word (e.g., "sacred"), a TLN created by transposing two-letters at interior locations (e.g., "scared"), and a control-word created by substituting between one- and three-letters at interior locations (e.g., "snared")[2]. Each word of the triplet was the same length. Lexical frequencies from the CELEX database (Baayen, Piepenbrock & Gulikers, 1995) for the TLN (*M*=26.8 counts/million) and control (*M*=21.7 counts/million) words did not differ (t<1) (see Appendix B).

Words from each set were inserted into an identical sentence frame so that either the TLN- or the control-word served as a prime and appeared a few words earlier in the same sentence as the target-word (e.g., "The man found the scared/snared animal and wrapped his sacred football shirt around it"). A pre-screen study using 72 participants (who did not participate in the eye movement experiment) confirmed that target-words were equally predictable, natural, understandable and plausible in sentences containing either a TLN or control prime word, and that the sentences did not differ in plausibility (*t*s<1) (see Table 2.1). Prime- and target-words were separated, on average, by 3.9 words (SD = 1.4; 18.7 (SD = 7.3) characters). The sentences were presented in counterbalanced lists so that for each participant, a sentence containing each target-word was presented only once, and an equal number of sentences containing either a TLN- or control-word prime were presented. The experiment therefore manipulated prime type (TLN, control) as a within-participants variable. The key dependent variables were eye movement measures for the prime-word, target-word, and post-target regions.

[2] Formal model comparisons between LME models that did and did not include a measure of orthographic overlap (the number of letters that varied between the target word and the prime) showed that this measure of orthographic overlap did not significantly improve the fit of the model to the data (Chi-squared test, all *p*s>0.2).

Table 2.1.Means (M) and standard deviations (SD) of the linguistic properties for the two types of word primes: transposed letter word (TL) and control; and of the sentence ratings. T-test comparisons showed no significant differences between TL and control primes in any of the lexical characteristics reported (*p* > 0.1), except for the number of orthographic neighbours (N) (*p* < .00). T-test comparisons also showed no significant differences between the two types of primes in any of the sentence ratings (*p* > 0.1). In addition, targets were also equally predictable following both types of primes (*p* > 0.4).

	TL		Control	
	M	SD	M	SD
Log Lexical Frequency (CELEX)	1.13	0.73	0.96	0.64
Neighbourhood density (N) (N_Watch)*	4.30	3.61	6.37	3.99
Imaginability (N_Watch)	491.5	117.26	549.69	72.71
AoA (Kuperman, Stadhaghen&Brysbaert, 2012)	6.91	1.59	6.42	1.84
Number of syllables (N_Watch)	1.37	0.56	1.27	0.45
SLFB (sum log bigram frequency; N_Watch)	11.38	2.32	11.87	1.84
MLFB (mean log bigram frequency; N_Watch)	2.8	0.34	2.94	0.28
Log Bigram Frequency X Position (CELEX)	3.55	0.55	3.38	0.95
Predictability	0.09	0.29	0.07	0.26
Plausibility (1-implausible to 5-plausible)	3.26	1.29	3.39	1.26
Understandability (1-easy to 5-difficult)	2.00	0.53	1.95	0.51
Naturalness (1-Unnatural to 5-natural)	3.40	0.52	3.46	0.50

Note. Formal lme comparisons between a simple model and a lme model including the N showed that N did not play any role in the observed findings (Chi-squared test, *p*>0.4). This demonstrates that neither the linguistic properties of the types of primes nor the sentence ratings impact on the findings observed in this study.

2.3.3. Apparatus and Procedure

An Eyelink-1000 eye-tracker recorded right eye movements. Forehead and chin rests were used to prevent head movements. Sentences were presented as black, Courier New, size-12-font on a grey-background on a 21” CRT monitor at a 60cm viewing distance. Participants were instructed to read normally and for comprehension. Once a participant finished reading a sentence, the participant pressed a response key, and 50% of the sentences were replaced by a comprehension question, to which the participant responded. The experiment lasted about 20 minutes.

2.4. Results

Comprehension accuracy was high (M=83%). Following standard procedures, fixations under 80ms and over 800ms were deleted, as were fixations more than 2.5 standard deviations from each participant per condition’s mean (less than 4%). In addition, short fixations (<80 ms), which were located within one character space of the next fixation, were merged into that nearby fixation. The data were log-transformed due to positive skew in the raw data. A range of eye-movement measures was computed for the prime-word, target-word, and post-target region (comprising the next word, or the next two words if the next word had fewer than four letters). For the prime and target words, we report first-fixation duration (duration of the first progressive fixation on a word), single-fixation duration (duration of the fixation on a word fixated only once during first-pass reading), gaze duration (sum of all first-pass fixations) total reading time (sum of all fixations), regressions-in (leftward saccades that land on the word), and second-pass reading time (the sum of fixations on a word following completion of first-pass reading of that word). In addition to these measures, for the target-word only we report regressions-out (backwards eye movements from the word) and regression path reading time, which is the time from the initial fixation on a word until the eyes move onward in the sentence

(Liversedge, Paterson & Pickering, 1998). The duration of the fixation immediately prior to the first-fixation on the target-word was also examined to ensure that effects at the target-word were not due to spillover effects from earlier text. Finally, for the post-target region, we report first-fixation duration, first-pass reading time (equivalent to gaze duration for a region containing more than one word), and regressions-out.

Data were analysed with linear mixed-effects (lme) modelling using the lme4.0 package (Bates, Maechler & Bolker, 2012) within R (R Development Core Team, 2013). For all analyses, prime (TLN, control word) was specified as a fixed factor, and participants and sentences were specified as random factors in a full random structure (Barr, Levy, Scheepers & Tily, 2013). The analyses were theoretically motivated, and we did not use any correction for multiple comparision due to they were planned comparisons indeed. Significance values, therefore, reflect both participant and sentence variability. Following convention, effects were considered significant when $t>2$. Table 2.2 shows means and standard errors for each measure.

2.4.1. Prime-Word

First-fixation durations were shorter for TLN prime- than control-words (b=.08, *SE*=.03; t=3.06). This effect was short-lived and not observed in later fixation time measures. It is consistent with facilitation of lexical access for TLN compared to control words, due to the activation of orthographically similar words. This is also consistent with facilitatory effects found with TLN of low frequency words in both lexical decision and naming tasks (Andrews, 1996; Experiments 1 and 2). In addition, second-pass reading times were longer for TLN than control words (b=-.14, *SE*=.07; t=-2.00), indicating that readers spent more time re-inspecting the TLN primes.

Table 2.2. Means (M) and standard errors (SE) for each condition: transposed letter neighbors (TL) and control words (Control), for each dependent variable in each region.

		TL		Control		
		M	*SE*	*M*	*SE*	
Prime Word	First Fixation Duration	228	4	251	6	*
	Gaze Duration	272	6	286	7	
	Single-Fixation Duration	250	8	275	10	
	Total Reading Time	468	15	469	14	
	Regressions In	0.34	0.02	0.35	0.02	
	Second-Pass Reading Time	454	24	400	21	*
Target Word	Duration of Fixation Prior to First Fixation on Target Word	210	4	215	4	
	First Fixation Duration	235	4	230	4	
	Gaze Duration	266	6	261	6	
	Single Fixation Duration	252	8	245	7	
	Total Reading Time	476	14	435	14	*
	Regression Path Reading Time	358	12	335	12	*
	Regressions Out	0.2	0.02	0.18	0.02	
	Regressions In	0.43	0.02	0.38	0.02	
	Second-Pass Reading Time	430	22	409	23	
Post-Target	First Fixation Duration	228	5	235	6	
	First-Pass Reading Time	305	10	299	9	
	Regressions Out	0.41	0.03	0.32	0.02	*

Note: (*) significant (t>2)

2.4.2. Target-Word

The duration of the fixation immediately prior to the first-fixation on the target-word showed no effects of the prime (b=.02, *SE*=.02; *t*=.87), indicating that processing of earlier text did not spillover to the target-word. No effects of the prime were observed in first-fixation duration, single-fixation duration, or gaze duration (bs<0.03, *t*s<1.13) either, indicating that the prime did not disrupt the initial processing of target-words. However, clear prime effects were observed in total reading time (b=-.10, *SE*=.04; *t*=-2.47) and regression path reading time (b=-.0.08, *SE*=.04; *t*=-2.14), due to increased reading times for target-words that followed a TLN- than a control-word. Crucially, the regression path effect indicated that the normal left-to-right progression of the eyes was impeded when the target followed a TLN-prime. Moreover, the total reading time effect indicated longer reading times following revisits to the target-word. No other effects were significant (bs<0.25, *t*s<0.9, *z*s<1.16)[3].

2.4.3. Post-Target Region.

No effects of the prime were obtained in first-fixation duration or first-pass reading time (bs<0.01, *t*s<0.34), indicating that target-word effects did not spillover to the post-target region. However, prime type affected regressions from this region (b=-.61, *SE*=.20; *z*=-3.08; *p*<.002), with more regressions when the target-word followed a TLN- than a control-word. This effect was consistent with misidentification of the target-word following a TLN (e.g., Johnson, 2009). No other effects were significant (bs<0.08, *t*s<1.71).

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[3] We also conducted formal comparisons of LME models with and without the relative frequency of the prime and target words, and found that including the relative frequency did not significantly improve the fit of the model to the data (Chi-squared test, all *p*s>0.1).

2.5. Discussion

The present findings show very clearly that prior exposure to a word's TLN earlier in the same sentence can interfere with the processing of that word during reading. This extends evidence of intra-sentential, inter-word lexical priming effects obtained previously for substitution-neighbors (Carreiras *et al.*, 2005; Frisson et al., 2014; Paterson *et al.*, 2009). Here, we show that this paradigm also produces effects between words that differ only in the order of two of their constituent letters.

An early facilitatory TLN effect also was found in first-fixation durations for the prime-words. This effect is likely to reflect the early co-activation of similar lexical representations (TLNs), which facilitated prime identification. Note that this effect occurred only at the prime-word, was short-lived, and did not spillover to affect target word processing. Furthermore, this effect was consistent with evidence from lexical and naming tasks, in which TLNs (of low frequency) are faster identified than their controls (Andrews, 1996; experiments 1 and 2).

Studies of inter-word priming during reading that used substitution-neighbors show early inhibitory effects on target-word processing (e.g., Paterson *et al.*, 2009). In the present experiment, inhibitory TLN effects at the target-word emerged only in regression path reading times, a measure of later processing. Regression path time includes fixations on the target-word along with any fixations on previous words until a fixation is made to the right of the target-word. Thus, a significant proportion of regression path time usually derives from fixations on words preceding the target-word (i.e., before the eye moves onwards in the sentence). No effect was obtained in gaze durations on target-words, so the regression-path effect must be driven by fixations that occurred after a regression from the target-word to re-read earlier parts of the sentence. Moreover, this increased re-reading must have been triggered at the target-word by prior exposure to its TLN. Two conclusions follow from this. First, in contrast to previous research with substitution-neighbors (e.g., Paterson *et al.*, 2009), prior exposure to a TLN appears not to have triggered lexical competition during target-word identification due to the lack of early effects on the target-word. Second, the disruption to processing we observed is consistent with readers initially misidentifying the target-word, potentially misreading it as the previously encountered TLN (e.g., Johnson, 2009). Such misidentification may have led to failure to integrate the target-word into the current sentence interpretation, resulting in processing disruption. For our example, "The man found the scared animal and wrapped his sacred football shirt around it", we are suggesting that readers initially misidentify the word "sacred" as the word "scared". However, this word does not fit the context, and so readers will detect this misidentification. Presumably, readers are aware that they recently encountered an orthographically similar word and so will often regress back to that word's location to verify if the prime and target are the same or slightly different words. Consistent with this explanation, we obtained a reliable inhibitory second-pass effect on prime words. In addition, we obtained an inhibitory TLN prime effect at the target-word in total reading times, indicating increased revisits to the target-word after initially encountering it. Presumably this effect reflects checking processes to confirm the identity of the prime-word relative to the target-word.

It could be argued that these effects reflect lexical competition late during lexical processing. For example, Perea and Pollatsek (1998) found inhibitory substitution-neighbor effects in total and regression path reading times for target-words, and also spillover effects and regressions back (to the target) fr a post-target region (see also Acha & Perea; Johnson, 2009). They argued that because the inhibitory effect was obtained in the first-fixation on the post-target region, this represented competition during later stages of lexical identification. In such a situation, lexical processing would be ongoing following initiation of a progressive saccade. In our experiment, neither early inhibitory

TLN effects at the target-words, nor spillover effects at the post-target region were observed, so it is unlikely that this account applies to the current findings. Instead, the misidentification account we propose seems more likely. This is also consistent with previous evidence that shows a lack of TLN effect using isolated-word paradigms (Castles *et al.*, 2003; Duñabeitia, Perea & Carreiras, 2009; Duñabeitia *et al.*, 2009; Perea *et al.*, 2008).

So why do TLNs, but not substitution-neighbors, cause post-lexical checking? First, TLNs share more orthographic information (an identical letter set) than substitution-neighbors (one letter different), and so are perceptually more confusable. This may increase the likelihood of misidentifying a TLN, producing increased post-lexical checking. Second, identification of the correct candidate may be inhibited at the target-word due to this word already being partially-activated when the prime was first encountered and identified. As already mentioned, an early facilitatory effect was found at the prime region, suggesting that having a TLN facilitates prime-identification. Once the prime was fixated and identified, the other member of the TLN pair (the target-word) will have been inhibited. Assuming prime activation remained greater than that associated with the target as the eyes progressed through the sentence, upon encountering the target, the prime would be more strongly activated than the target. This, in turn, may trigger misidentification of the target as the prime. Indeed, this second possibility is consistent with an episodic memory approach to word recognition (e.g., Tenpenny, 1995), which assumes that, when the same (or similar) word is presented repeatedly, the word is identified faster because episodic memory traces associated with its prior encounters are evoked. But, whatever the exact explanation, it is clear that prior exposure, and therefore identification, of a word's TLN caused disruption to the processing of that word due to its misidentification, triggering post-lexical checking.

Computational models of isolated-word recognition cannot readily explain post-lexical checking during reading, quite reasonably, because they were designed primarily to explain lexical identification of isolated-words. Some computational models of eye-movements during reading distinguish between lexical and post-lexical processing (e.g., the E-Z Reader Model, see Reichle, 2011). However, the nature of lexical processing in such models remains underspecified; quite reasonably, given that the primary objective of these models is to account for eye-movement control and not word recognition. In our view, this reflects the current position in understanding the processes underlying reading, and researchers (including ourselves) seeking a fuller understanding of these processes must develop accounts of lexical processing that can be realistically incorporated into models of eye-movement control. Such accounts would aim to explain how lexical processing is distributed across successive fixations and employs both partial (parafoveal), as well as fully available (foveal) visual information for word recognition (see Rayner & Liversedge, 2011; Grainger, 2000, for similar views).

In summary, the present study provides novel findings relating to TLN intra-sentential, inter-lexical priming during reading. We show evidence of TLN influences at a prime-word early in the sentence, and effects consistent with lexical misidentification of a TLN target-word downstream in the sentence. Overall, the present findings reveal more fully how the orthographic-neighborhood impacts on lexical and post-lexical processing during reading.

Finally, for future research, and to replicate this pattern of data, it should be considered to use a more direct test that provide direct evidence of the fact that late inhibitory effects are a consequence of initial misidentifications rather than lexical competition. For example, it would be interesting to examine whether readers misidentify TLN when they read aloud the sentences.

Chapter 3: Parafoveal pre-processing of word initial trigrams during reading in adults and children

The contents of this chapter are a minor revision of Pagán, Blythe & Liversedge (2015) accepted in the *Journal of Experimental Psychology: Learning, Memory and Cognition*[4]. In press.

3.1. Abstract

Although previous research has shown that letter position information for the first letter of a parafoveal word is encoded less flexibly than internal word beginning letters (Johnson, Perea & Rayner, 2007; White et al., 2008), it is not clear how positional encoding operates over the initial trigram in English. This experiment explored the pre-processing of letter identity and position information of a parafoveal word's initial trigram by adults and children using the boundary paradigm during normal sentence reading. Seven previews were generated: Identity (*captain*); transposed letter and substituted letter nonwords in position 1&2 (*acptain-imptain*); 1&3 (*pactain-gartain*) and 2&3 (*cpatain-cgotain*). Results showed a transposed letter effect (TLE) in position 13 for gaze duration in the pre-target word; and TLE in position 12 and 23 but not in position 13 in the target word for both adults and children. These findings suggest that children, similar to adults, extract letter identity and position information flexibly using a spatial coding mechanism; supporting isolated word recognition models such as SOLAR (Davis, 1999, 2010) and SERIOL (Whitney, 2001) models.

[4]Experimental design, data collection, analyses and write-up were completed by Ascensión Pagán under the supervision of Hazel Blythe and Simon Liversedge.

3.2. Introduction

The purpose of this study was to examine how letter identity and position information are encoded during lexical identification in sentence reading by children and adults. Specifically, in this study, parafoveal pre-processing of letter identity and position information in a word's initial trigram by children and adults during silent sentence reading was explored.

3.2.1. Parafoveal pre-processing in children and adults

Research in parafoveal pre-processing in adults, using gaze-contingent change paradigms (McConkie & Rayner, 1975; Rayner, 1975), has shown that readers not only process the fixated word but also extract some visual and linguistic information from the next word in the sentence, before it is directly fixated (see Schotter, Angele & Rayner, 2012 for a review). Studies using the moving window paradigm have shown that in skilled readers, the effective visual field in reading (the perceptual span) extends over an asymmetrical area from 3-4 characters spaces to the left of the fixated word to 14-15 character spaces to the right of fixation in alphabetic languages (McConkie & Rayner, 1975). Word identification occurs in the area closest to fixation (between 3-4 letters to the left and 6-7 letters to the right of fixation) (Rayner & Bertera, 1979; Rayner, Inhoff, Morrison, Slowiaczek, & Bertera, 1981).

With respect to the size of the effective visual field in reading for children, studies have shown that the perceptual span increases with age. Thus, 7- to 9-year-old children were found to have a perceptual span of 3-4 letter spaces to the left of fixation and 11 letters to the right; while the span was 3-4 letters spaces to the left and 9 letters to the right of fixation in 11-year-old children (Häikiö, Bertram, Hyönä & Niemi, 2009; Rayner, 1986; Sperlich, Schad & Laubrock, 2015; see also Henderson & Ferreira, 1990). These age-related changes in the size of the perceptual span were primarily attributed to differences in processing difficulty. Rayner (1986) showed that when the difficulty of the text was increased, sixth grade children had a reduced perceptual span. In addition, Häikiö *et al.* (2009) found that the number of letters that could be identified during a fixation (the letter identity span) was smaller for slower readers (within all ages included in their sample) than for faster readers. In summary, these studies show that the perceptual span increases with age as a result of the reader's increasing skill and, hence, decreasing processing difficulty, when reading.

Researchers typically use the boundary paradigm in order to examine the particular nature of information that is extracted from a parafoveal word before it is fixated (McConkie & Rayner, 1975; Rayner, 1975). By comparing fixation times on the target word as a function of the preview condition, it is possible to determine the type of information that is pre-processed in the parafovea. A large body of evidence has showed that skilled adult readers pre-process information regarding word spacing (Epelboim, Booth, Ashkenazy, Taleghani, 1997; Johnson & Eisler, 2012; Johnson, Perea & Rayner, 2007; Malt & Seamon, 1978; McConkie & Rayner, 1975; Morris, Rayner & Pollatsek, 1990; Perea & Acha, 2009a; Pollatsek & Rayner, 1982; Rayner, Fisher & Pollatsek, 1998; Spragins, Lefton & Fisher, 1976; White, Johnson, Liversedge & Rayner, 2008), word length (Inhoff, Starr, Liu & Wang, 1998; Inhoff, Eiter, Radach & Juhasz, 2003), orthography (at least partially; Binder, Pollatsek & Rayner, 1999; Johnson & Dunne, 2012; McConkie & Zola, 1979; Rayner, McConkie & Zola, 1980) and phonology (Ashby & Rayner, 2004; Chace, Rayner & Well, 2005; Henderson, Dixon, Petersen, Twilley & Ferreira, 1995; Pollatsek, Lesch, Morris & Rayner, 1992). To date, however, no research has been conducted to examine developmental changes in parafoveal processing dependent upon the type of information (e.g., orthographic, phonological, semantic) that can be extracted from the word to the right of fixation. Three studies have used the boundary paradigm with children, all in languages other than English (Häikiö, Bertram & Hyönä, 2010 in Finish; Tiffin-Richards & Schroeder, 2015 and Marx, Hawelka, Schuster & Hutzler, 2015 in German). These studies showed that, despite the fact that children have a reduced perceptual span compared to adults, they do pre-processes information from the word to the right of fixation. In the present study, the boundary paradigm was used to investigate how pre-processing of letter identity and position information within a word's initial trigram affects lexical processing in children compared to adults.

3.2.2. The transposed letter effect

There are a fixed number of letters in an alphabetic orthography (e.g., the alphabet has 26 letters in English and 27 in Spanish), which are combined in different ways to form words. Thus, it is crucial to know both the identity and the position of each letter in a sequence in order to select the appropriate lexical candidate (for example, to discriminate between "*calm*" and "*clam*"; "*pots*" and "*post*"). Recently, interest in the study of how letter position information is represented within lexical representations has increased considerably (see Grainger, 2008 for a review), particularly as a result of empirical evidence from the transposed letter effect.

The transposed letter effect refers to the finding that nonwords which have been created by switching the positions of two letters within a word (e.g. "*jugde*") can activate the orthographic representation of the original word ("*judge"*) such that the original word´s identification time (typically in an isolated word recognition task, such as masked priming with a lexical decision task) is reduced in comparison to when the nonword primes have been created by letter substitutions ("*junpe*"). This effect has been observed both in adults (e.g., Andrews, 1996; Acha & Perea, 2008b; 2010; Bruner & O'Dowd, 1958; Chambers, 1979; Christianson, Johnson & Rayner, 2005; Foster, Davis, Schoknecht & Carter, 1987; García-Orza, Perea & Muñoz, 2010; Holmes & Ng, 1993; Johnson & Dunne, 2012; Kinoshita & Norris, 2009; Lupker, Perea, & Davis, 2008; O'Connor & Forster, 1981; Perea & Acha, 2009b; Perea & Carreiras, 2006a, 2006b, 2006c, 2008; Perea & Lupker, 2003a, 2003b, 2004, 2007; Perea, Abu Mallouh & Carreiras, 2010; Perea, Duñabeitia & Carreiras, 2008; Perea & Pérez, 2009; Perea, Winskel & Ratitamkul, 2012; Schoonbaert & Grainger, 2004; Taft & Graan, 1998; Velan & Frost, 2011) and in children (Acha & Perea, 2008a; Castles, Davis, Cavalot & Forster, 2007; Kohnen & Castles, 2013; Lété & Fayol, 2013; Paterson, Read, McGowan & Jordan, 2015; Perea & Estévez, 2008; Tiffin-Richards & Schroeder, 2015). Transposed letter effects have also been reported for silent sentence reading (see Acha & Perea, 2008b; Blythe, Johnson, Liversedge & Rayner, 2014; Johnson, 2007, 2009; Johnson & Dunne, 2012; Johnson & Eisler, 2012; Johnson, Perea & Rayner, 2007; Perea, Nakatani & van Leeuwen, 2011; Rayner, White, Johnson & Liversedge, 2006; Tiffin-Richards & Schroeder, 2015; White, Johnson, Liversedge & Rayner, 2008).

In the following section, the means by which the most representative models of isolated word recognition explain letter position encoding in the lexicon will be explained. Note, however, that these models were designed to explain lexical identification only in the case of isolated words presented in the fovea (e.g., data from lexical decision-type tasks), and they are not intended to explain how lexical identification occurs in sentence reading; nor whether the letter identity and position information encoding imply the same visual processes in foveal and parafoveal vision. On the other hand, eye movement models of reading such as E-Z Reader (Reichle, 2011) and SWIFT (Engbert & Kliegl, 2011) do not specify how letter position encoding occurs during lexical processing in sentence reading. They, however, can account for different foveal and parafoveal processing in adults and children. Given the lack of models for letter position encoding within sentence reading, a number of hypotheses will be presented for the present experiment based upon inferences from these single word recognition models. We will investigate the extent to which these models can also explain letter position encoding during lexical identification in sentence reading, and we will address how eye movement models of reading should take into consideration letter position encoding during lexical processing in sentence reading by both adults and children.

3.2.3. Models of Letter Position Encoding

The transposed letter effect (the greater similarity of a TL nonword than a SL nonword to the base word) has challenged traditional visual word recognition models such as the Interactive Activation model (McClelland & Rumelhart, 1981); the Dual Route Cascaded model (Coltheart et al., 2001); the Multiple Read-Out model (Grainger & Jacobs, 1996); the activation-verification model (Paap, Newsome, McDonald & Schvaneveldt, 1982), and the Parallel Distributed Processing model (Harm & Seidenberg, 1999). These models propose that both letter identity and position information are encoded at the same time (a slot coding schedule; e.g., in "*state*" there are different nodes to represent the same letter, "t", in different positions: S_1, T_2, A_3, T_4 and E_5). According to these models, a transposition (where two letters change positions) should be just as disruptive as a double substitution. The transposed letter effect shows clearly, however, that transposed letter (TL) nonwords are more similar to their base word than substituted letter (SL) nonwords, even when only one letter is substituted (see Perea & Lupker, 2003).

Newer models of visual word recognition, such as the SOLAR model (Davis, 1999, 2010); the Open Bigram model (Grainger & van Heuven, 2003; Grainger, Granier, Fariolli, van Assche & van Heuven, 2006); the Overlap model (Gómez, Ratcliff & Perea, 2008); and the SERIOL model (Whitney, 2001) incorporate more flexible mechanisms to encode letter position information. In these more recent models, letter identity and position information are encoded independently; the different mechanisms by which each of these models accounts for the transposed letter effect will be described next. The "Overlap model" (Gómez *et al.*, 2008), which has adapted one assumption from the "Bayesian Reader" (Norris, 2006), assumes that when the string is presented briefly, the position that corresponds to each letter in the sequence is not precisely encoded and as a result, the visual information which corresponds to each letter is distributed over the entire word space (*position uncertainty assumption*). For example, in the word "CALM", the letter "C" will have a peak of activation in the first position which then decreases monotonically across the other positions to the right. The letter "L" will have its peak of activation in the third position, decreasing over the other letter positions on both sides: the first, second, and fourth will all be slightly activated (but less than the third).

Other models, such as the Open Bigram (Grainger & van Heuven, 2003; see also Grainger *et al.*, 2006) and the SERIOL model (Whitney, 2001) assume that letter position is encoded through contextual information. For example, in the word "CALM" the bigrams (adjacent or non-adjacent pairs of letters) that form the word are CA, AL, LM, CL, CM and AM. In both models, adjacent bigrams are more activated than non-adjacent bigrams (e.g., CA > CL or CM; AL > AM). In addition, the SERIOL model assumes also a spatial coding mechanism whereby, in a four letter word for instance, the bigram that appears in the first position receives the most activation while the bigram which appears in the second position is the second most activated, and so on (e.g., CA > AL > LM). Finally, the SOLAR model (Davis, 1999, 2010) also assumes a spatial coding mechanism as in the SERIOL model but without taking into account contextual information (bigram); it uses single letters. In this case, the word "CALM" would be represented as C > A > L > M. While all these recent models are able to explain the transposed letter effect, the differences between them are mainly based on the level of representation (letters vs. bigrams) and the mechanism used to encode letter identity and position information (slot, contextual or spatial coding).

3.2.4. Internal vs. external letter transpositions

Empirical evidence from isolated word recognition has shown that manipulations involving the first letter of the word do not cause a transposed letter effect: nonwords with transposed letters (demula-MEDULA) were equally effective primes for the base word as were nonwords with two substituted letters in the same positions (berula-MEDULA) (e.g., Perea & Lupker, 2004, 2007; Schoonbaert & Grainger, 2004). In addition, the size of the transposed letter effect has been found to be greater when the manipulated letters are internal (29 ms) than when they are external (9 ms) (Perea & Lupker, 2003a, 2003b). Similarly, evidence from silent sentence reading has shown that the cost associated with reading directly fixated transposed letter strings decreased for internal letter manipulations compared to those involving initial or final letters (Rayner *et al.*, 2006); specifically, the greatest cost to reading times occurred in those sentences where initial letters were transposed in comparison to internal letters (Jonhson, 2007; Johnson & Dunne, 2012; Johnson & Eisler, 2012; White *et al.*, 2008; see also Briihl & Inhoff, 1995; Jordan, Thomas, Patching & Scott-Brown, 2003; Plummer & Rayner, 2012; Rayner et al., 1980; Tiffin-Richards & Schroeder, 2015). Finally, Johnson *et al.* (2007) used the boundary paradigm to manipulate the parafoveal preview of internal versus final letters (Experiment 2) and initial versus final letters (Experiment 3). They found a transposed letter effect for internal letters but not for final letters (Exp. 2). In Experiment 3, they found a transposed letter effect for letters 1 and 2 in gaze duration (reliable only by participants, not by items) and a non-significant, numerical tendency of about 10 ms in both first and single fixation duration. These data also support the argument that very early in lexical processing, during parafoveal preview, the positional information of a word's initial letters is not encoded as flexibly as is the case for a word's internal letters.

In summary, evidence from isolated word recognition and reading shows that internal letter identity and position information is encoded flexibly while initial letter identity and position information is encoded more strictly, presumably, due to its special role as a lexical access unit to facilitate word identification. Consistent with this empirical evidence, models based on flexible letter position encoding assume that initial letters are encoded less flexibly than internal letters and predict a smaller transposed letter effect, or no transposed letter effect at all, for manipulations of the first letter.

3.2.5. The transposed letter effect in children

Only a few studies have examined the transposed letter effect in children and these have all used isolated word recognition tasks such as lexical decision (with and without masked priming techniques) and naming (Acha & Perea, 2008b; Perea & Estévez, 2008). Only one study in German by Tiffin-Richards and Schroeder (2015), using the boundary paradigm, has examined the transposed letter effect in children compared to adults during sentence reading. They found that 8-9 years old children showed a transposed letter effect when the letters manipulated were in position 12 ("*Arnd*" vs. "*Urnd*"- *Rand* (base word)) and 23 ("*Rnad*" vs. "*Rcod*") in single fixation duration; however, the effect was not found in any other measure and they argue that it should be "interpreted with caution" given that beginning readers make relatively few single fixations when reading. In contrast, adults showed a robust transposed letter effect when the letters manipulated were in position 23, but not in position 12, in single fixation, first fixation and gaze duration. To date, however, no studies have examined the transposed letter effect in children's silent sentence reading in English. It is clear, however, that children are sensitive to manipulations of the external letters of words during reading. In 1975, Rayner and Kaiser studied whether the cost of altering a word's letters was dependent upon their position within the word for 6th grade children during a reading aloud task. They found that those texts with visually dissimilar substituted letters at the beginning of a word (e.g., "*yorld*") caused a greater cost to reading than texts with dissimilar substituted letters in the middle or at the end of the word (e.g.,"*wogld*" or "*worlr*"), indicating the important role of word-initial letters for lexical identification during text reading in children.

A few studies have shown a transposed letter effect for internal letters early in the acquisition of reading, indicating that 7-9 years old children encode letter position information in a flexible manner, similar to adults (Acha & Perea, 2008b; Perea & Estévez, 2008; see also Castles, Davis & Forster, 1999; Castles *et al.*, 2007). More importantly, the only difference found between adults and children in these studies was in the magnitude of the transposed letter effect. The advantage associated with transposed (compared to substituted) letters was found to be greater for 7-9 years old readers than for 10-11 years old children or adult (no differences were found between 10-11 years old children and adults). This suggests that orthographic representations are less precisely encoded in 7-9 years old children than in adults (see also the Lexical Quality Hypothesis by Perfetti & Hart, 2001, 2002; Perfetti, 2007). Furthermore, the difference in the magnitude of the transposed letter effect between adults and children has been interpreted as a change in the tuning of the word recognition system (e.g. Castles *et al.*, 2007). At an early stage of reading, with a relatively small vocabulary stored in the orthographic lexicon, the process of lexical identification is quite flexible due to the reduced requirement for a well-specified representation of the orthographic forms of words. Specifically, because beginning readers only recognise the printed forms of a relatively small number of words, there are fewer inhibitory influences from competitor words during lexical identification, and so it is possible for identification to occur on the basis of a less precise overlap of the orthographic form of the input letter string (e.g. Castles, Holmes & Wong, 1997; Treiman, Goswami & Bruck, 1990). In later stages, as vocabulary size increases, however, the lexical identification system has to be more precisely tuned in order to accurately distinguish between orthographically similar words and to correctly identify the input letter string (see also Share, 2005). Such a developmental change in the tuning of the lexical identification process would explain why letter position encoding might be more flexible in beginning readers compared to more skilled readers, and would also explain why factors such as vocabulary size, word length and neighbour density also modulate the magnitude of the transposed letter effect (Acha & Perea, 2008b; Castles *et al.*, 1999, 2007).

One of the limitations of the flexible letter position encoding models described above is that they cannot account for differences in the magnitude of the transposed letter effect between adults and children because, for example, they are not able to learn (Acha & Perea, 2008b). Furthermore, flexible letter position encoding models assume that the transposed letter effect reflects the noisy operation of the position-coding mechanism and, thus, is not influenced by reading development (see Gómez *et al*., 2008; Norris, Kinoshita & van Casteren, 2010).

3.2.6. Grainger and Ziegler´s model (2011)

In Grainger and Ziegler´s model (2011), two sublexical orthographic codes are postulated which differ in terms of their level of precision of letter position encoding. In addition, these codes vary in their mapping of orthography either (1) directly onto semantic representations or (2) onto sublexical morphological and phonological representations which are already stored in the lexicon, and from there to semantics. These two codes are generated within what are termed the coarse-grained route and the fine-grained route, respectively. This model accounts for lexical identification in skilled readers (specifically, those who are beyond overt, effortful phonological decoding); there are, however, important developmental changes proposed within this model and we return to this point later.

In the coarse-grained route, letter position is encoded through an "Open Bigram" mechanism, in which ordered pairs of letters are encoded independently of their contiguity (as per Grainger & van Heuven, 2003). A relatively fast "guess" at whole word identity is generated on the basis of the identity and order of the most visible letters (in terms of retinotopic position), providing direct access from orthography to semantics. The existence of such a route is supported by all the studies using transposed letter masked priming studies (see Grainger, 2008 for a review). Furthermore, the use of this route could also account for similar effects within parafoveal preview, as reported from sentence reading studies (e.g., Johnson *et al.*, 2007). It is not possible, however, that such a coarse-grained orthographic code could activate pre-existing phonological and morphological sublexical representations because these require the encoding of specific letter position information (note that a number of studies have demonstrated pre-lexical phonological and morphological effects). Such processing is accounted for within the fine-grained route. The fine-grained route transforms the visual input into orthographic representations of contiguous, multi-letter graphemes (e.g., sh, th, ph) and morphemes (e.g., ing, er, re) to access semantics. Thus, orthographic encoding through this fine-grained route provides no flexibility in terms of letter position encoding, but does offer a means of accounting for effects such as the pseudo-homophone advantage (Rastle & Brysbaert, 2006 for a review) and morphological priming (see Rastle & Davis, 2008 for a review). Again, the existence of such a fine-grained route could also account for such effects in parafoveal pre-processing during sentence reading (e.g., Henderson *et al.*, 1995; Lima & Inhoff, 1985; Miellet & Sparrow, 2004).

With respect to developmental changes, this model proposes three broad stages of lexical identification. First, serial processing of the letters within a word occurs via phonological coding. Note that this stage is not incorporated in the main model as such but is considered a necessary precursor, analogous to the self-teaching mechanism proposed by Share (1995; see also Ehri, 2005). From this "laborious serial procedure", parallel orthographic encoding of the letters within a word occurs in Stage 2 through the development of position-specific letter detectors. Finally, in Stage 3, the two routes for orthographic encoding develop that form the basis of skilled silent word reading.

A complementary prediction can be made for developmental changes in the transposed letter effect, on the basis of more traditional theories of children's literacy development. Such models (e.g., Ehri, 2005), under the assumption of the Lexical Quality Hypothesis (Perfetti & Hart, 2001, 2002; Perfetti, 2007), predict that the size of the transposed letter effect should decrease with greater reading experience and vocabulary sizes because orthographic representations become more precisely encoded (fine-tuning hypothesis) in order to discriminate between words (see Castles *et al.*, 2007; Castles, Davis & Lechter, 1999), resulting in greater inhibitory transposed letter priming effects in skilled readers when the primes are words (Andrews and Lo, 2012).

In summary, there are models of orthographic processing that can account for flexible letter position coding and the transposed letter effect in adults, but not children (Davis, 1999, 2010; Whitney, 2001; Grainger *et al.*, 2006; Gomez *et al.*, 2008). There are models that can account for developmental differences between adults and children more broadly in terms of the phases of literacy acquisition (see Ehri, 2005 for a review), but these theories result in predictions concerning the transposed letter effect that conflict with the experimental literature in this area though (of course, these models were not intended to account for flexible letter position encoding effects).

3.2.7. Letter position encoding of a word's initial trigram

The empirical evidence from both isolated word recognition and sentence reading research indicates that position information for the first letter of a word is crucial for lexical identification and is encoded in a strict manner, in children and adults, in order to access the correct lexical representation. Some studies have examined parafoveal processing of the initial trigram to explore the type of information than can be extracted from the parafovea, and letter position encoding, in adults (e.g., Briihl & Inhoff, 1995; Johnson *et al.,* 2007; Plummer & Rayner, 2012; Tiffin-Richards & Schroeder, 2015; White *et al.,* 2008); to date, however, no study has examined how letter position information for a word's initial trigram is encoded in parafoveal preview for a word's initial trigram by children in English. This is important because letter position encoding over a word's initial trigram provides important information concerning aspects of lexical identification: the nature of the lexical access unit that is used to facilitate word identification (letter or bigram); how position information is encoded (strictly or flexibly); and the mechanism used to encode position information (slot, contextual or spatial coding). Furthermore, investigating the transposed letter effect in children provides a better understanding about the developmental changes in word identification and, more specifically, whether there is a change in the process by which the visual word recognition system encodes letter position information.

In the present invisible boundary experiment, parafoveal pre-processing of letter identity and position information for the initial word's trigram was explored in both adults and children during silent sentence reading. We investigated which of the initial trigram's features (letter identity, or position, or both) are extracted from the parafovea during sentence reading, and the time course over which such processing occurs.

In this experiment, three key theoretical questions were addressed: (1) whether a word's initial letters (for example, letters 1&2) are encoded less flexibly than internal letters (letters 2&3); (2) whether such processing operates over individual letters (1&2 and 1&3 conditions will be similar), or over bigrams (no differences between 1&2 and 2&3 conditions), such that either the first letter or the first bigram of a word is crucial for the identification of that word due to its role as an access unit; and (3) whether such processing occurs differentially in children compared to skilled adult readers. In order to examine these issues, the boundary paradigm was employed within a silent sentence reading task, and two variables were manipulated: the type of preview (identity vs. transposed letters vs. substituted letters) and the position of the manipulated letters (1&2 vs. 1&3 vs. 2&3).

Three predictions were made with respect to the data from our adult participant group. First, that the identity condition would produce the shortest reading times compared to all other conditions, indicating that both letter identity and position information are extracted from the parafovea (as per Johnson *et al.*, 2007). Second, that a transposed letter preview would result in shorter fixation times on the target word than a substituted letter preview, suggesting that letter identity information is extracted from the parafovea independent of letter position information. Such a pattern would support flexible letter position coding models such as Overlap (Gómez *et al.*, 2008), Open Bigram (Grainger *et al.*, 2006), SOLAR (Davis, 1999, 2010) and SERIOL (Whitney, 2001). Third, there were two likely alternative patterns of effects with respect to the particular letters within a word which were manipulated. In one case, there might be little or no transposed letter effect when the first letter was manipulated, but a robust transposed letter effect when only internal letters were manipulated (as reported in Experiment 3 by Johnson *et al.*, 2007; Perea & Lupker, 2007; White *et al.*, 2008). This pattern of results would support those models which propose that both letter identity and letter position information for the first letter are encoded strictly due to its special role as lexical access unit (Overlap, Gómez *et al.*, 2008, and SOLAR, Davis, 1999, 2010, models). Alternatively, there might be a transposed letter effect for both positions 1&2 and 2&3 but not in 1&3. This latter possibility would indicate that relative letter position information is extracted from the parafovea, e.g., that the letters of the word are encoded as bigram units, and would support contextual coding models (Open Bigram, Grainger *et al.*, 2006, and SERIOL, Whitney, 2001 models). Furthermore, considering this latter possibility of bigram coding, the SERIOL model would predict that the transposed letter effect for position 1&2 should be of a smaller magnitude than for position 2&3 due to its special role as lexical access unit (Whitney, 2001). The Open Bigram model does not make this distinction (Grainger *et al.*, 2006).

Importantly, we assume that the extraction of letter identity and position information from the parafovea is not a categorical process in which a feature is either extracted or it is not, but is a continuous process where the extent to which different features are extracted will depend on the time course of processing of the word during fixations on the preceding word (e.g. Henderson & Ferreira, 1990; White, Rayner & Liversedge, 2005a). Thus, the time course of letter position encoding will be explored. It may be the case that letter position information is extracted early, even before the word is directly fixated and influences fixation times on the pre-target word depending on the location of the letters manipulated within the word.

We also made six predictions with respect to the data from our child participant group. First, we predicted overall longer reading times on the target words for children compared to adults (Blythe & Joseph, 2011). Second, we predicted that children would have their shortest reading times in the identity condition compared to the transposed and substituted letter conditions, indicating that letter identity and position information are extracted from the parafovea by children as well as by adults (see Rayner, 1986; Häikiö et al., 2010; Tiffin-Richards & Schroeder, 2015). Third, consistent with the literature, we predicted a transposed letter effect such that the transposed letter condition would result in shorter reading times than the substituted letter condition, because children are thought to encode letter position information flexibly as is the case with adult readers (Acha & Perea, 2008b; Castles *et al.*, 1999, 2007; Tiffin-Richards & Schroeder, 2015). The isolated word recognition literature has documented that beginning readers showed a greater transposed letter effect than adults; fourth, therefore, we predicted an interaction between our manipulation of letter position and participant group such that the TLE would be of greater magnitude in 8-9 years old children than in adults (e.g., Acha & Perea, 2008b; Perea & Estévez, 2008). Fifth, most evidence concerning the TLE effect in children has resulted from experiments making internal letter manipulations (Acha & Perea, 2008b; Perea & Estévez, 2008). On the basis of these experiments, we predicted a transposed letter effect in our child participants for the internal letter manipulation (2&3). Finally, with respect to initial letter manipulations (1&2 and 1&3) in children there were, again, two different possibilities. One possibility was the observation of a similar pattern for both these conditions suggesting that letter identity and position information for the first letter are encoded strictly in children. Alternatively, a transposed letter effect for letters 1&2 but not 1&3 would suggest that children encode relative letter position information (e.g., bigrams), supporting contextual coding models such as the Open Bigram (Grainger *et al.*, 2006) and SERIOL (Whitney, 2001) models. This latter possibility would also support Grainger and Ziegler's model (2011), indicating that children in Year 4 are able to use the coarse-grained orthographic route.

3.3. Method

3.3.1. Participants

A total of 84 participants (42 children and 42 adults) took part in this experiment. The children were recruited from Year 4 of primary schools in and near Southampton, and had a mean age of 9 years (range = 8.1 - 9.6; *SD* = 0.5). Year 4 children were recruited to ensure that they could benefit from parafoveal processing. At this age, most children are capable of pre-processing information from the word to the right of fixation (Rayner, 1986; Häikiö *et al.,* 2009, 2010). The adult participants were from the University of Southampton, and had a mean age of 19.6 years (range = 18 - 26; *SD* = 1.6). All participants had normal or corrected to normal vision, and were native speakers of English with no known reading difficulties. Furthermore, pre-screening with the READING subtest of the Wechsler Individual Achievement Test II (WIAT-II; Wechsler, 2005) confirmed that no participants showed evidence of reading difficulties (composite standardized score for adults: *M* = 117; *SD* = 5.8 (range: 106 - 130); and for children: *M* = 111; *SD* = 8.4 (range: 94 - 127). They were unaware of the purpose of the experiment until afterwards. University students received course credits as a reward for participating.

3.3.2. Apparatus

The sentences were presented on a 21" CRT monitor, set at a refresh rate of 120 Hz with a 1024x768 resolution, interfaced with a PC at a viewing distance of 60 cm. An eye contingent boundary technique was used (Rayner, 1975) where the display changes occurred within 10 ms of the eye crossing the boundary. Sentences were presented in black, Courier New, size 12 font on a grey background; three characters subtended 1° of visual angle. Although reading was binocular, eye movements were recorded only from the right eye, using an EyeLink 1000 tracker (S.R. Research Ltd.), with forehead and chin rests in order to minimize head movements. The spatial resolution of the eye tracker was 0.05º, and the sampling rate was 2000 Hz.

Word reading, pseudoword decoding and reading comprehension for each participant were assessed using the WIAT-II (Wechsler, 2005).

3.3.3. Material and design

Fifty-six experimental sentences containing a 6-7 letter target word were specially constructed. Target words (nouns or adjectives) were bisyllabic with a CVC structure for the initial trigram, which was within the same syllabic unit (e.g., *captain*). These target words had fewer than three orthographic neighbours, and had a mean of Age of Acquisition of 6.78 years (*SD* = 1.70) (Kuperman, Stadthagen-Gonzalez & Brysbaert, 2012). Target word frequency was in a range between three and 276 per million using child frequency counts (*M* = 37, *SD* = 53) (Children's Printed Word Database; Masterson, Dixon & Stuart, 2003) and in a range between 0.61 and 3483 per million using adult frequency counts (*M* = 179, *SD* = 559) (English Lexicon Project Database; HAL corpus, Balota et al., 2007). Pre-target words were mainly adjectives between 3 and 7 letters long (M = 5) (see Appendix B).

Seven parafoveal preview conditions were generated for each target word (see Appendix B). In the identity condition, the preview was the same as the target word (*captain*). In the transposed letter (TL) conditions, the positions of two letters were switched; in the substituted letter (SL) conditions, two letters were replaced with similar letters (ascenders with ascenders, descenders with descenders, consonants with consonants and vowels with vowels). The position of the transposition or the substitution was also manipulated, such that it occurred in the following positions: one and two (12; a*cptain* vs.

imptain); one and three (13; *pactain* vs. *gartain*); or two and three (23; *cpatain* vs. *cgotain*) (see Figure 3.1). Bigram and trigram frequency were calculated using CELEX database (CELEX database; Baayen, Piepenbrock & Gulikers, 1995). We estimated the number of times that specific letters in the critical positions (12, 13 and 23) appeared in the same position in other words. Bigram frequencies (in manipulated positions) and initial trigram frequency for transposed and substituted letter nonwords did not differ significantly across the experimental conditions (*t*s < 1) (see White, 2008 for a similar approach).

Figure 3.1. Example of an experimental sentence with the seven parafoveal preview conditions that were generated for each target word and where the invisible boundary was set for each sentence in this experiment. (*) refers to a fixation.

Example

```
1. Kelly always chooses her lucky| number to play the lottery. (Identity)
2. Kelly always chooses her lucky| unmber to play the lottery. (TL-12)
3. Kelly always chooses her lucky| acmber to play the lottery. (SL-12)
4. Kelly always chooses her lucky| munber to play the lottery. (TL-13)
5. Kelly always chooses her lucky| rusber to play the lottery. (SL-13)
6. Kelly always chooses her lucky| nmuber to play the lottery. (TL-23)
7. Kelly always chooses her lucky| nseber to play the lottery. (SL-23)
                                *|
```

To confirm that our target words were known to children in our selected age range as well as to ensure that our sentences were more generally age-appropriate, we undertook a pre-screening procedure. Two sentences were created for each target word to be rated (112 sentences), in order to select a final subset for the eye movement experiment (selecting just one of the two possible sentences per target word). We asked 24 children (Year 4: 8-9 years old) to rate our sentences on a scale of 1 (easy to understand) to 7 (difficult to understand). The final subset of sentences was rated as easy to understand (*M* = 1.14, range = 1.0-1.6). None of the children in this pre-screening study took part in the main eye tracking experiment.

The final set of 56 experimental sentences was counterbalanced across seven lists using a Latin Square design. Each list was read by 12 participants (six adults and six children). Each list included nine practice sentences, and 56 experimental sentences (eight sentences per condition). The sentences occupied one line on the screen (maximum = 60 characters; *M* = 58 characters) and the target word appeared in the middle of the sentence. The experimental sentences were presented in a random order to each participant.

3.3.4. Procedure

The three reading subtests- word reading, pseudoword reading and comprehension- of the WIAT-II were completed first, to confirm that our participants had no reading difficulties. Then, the eye movement experiment was conducted. Participants were instructed to read each sentence for comprehension. After each sentence, the participant had to press a button on the game controller to continue and, following 50% of the sentences, to answer Yes/No to comprehension questions. Participants were free to take a break whenever they wished, and could withdraw from the experiment at any point. After the experiment, the participants were asked whether or not they had noticed anything strange about the appearance of the text in the experiment because detecting a display change can affect fixation times (Slattery, Angele & Rayner, 2011; White, Rayner & Liversedge, 2005a). Only one participant was replaced because he/she reported noticing more than three changes. The experiment lasted about 40 minutes.

3.4. Results

All participants scored at least 75% on the comprehension questions (adults: *M* = 98%, *SD* = 2.51%; children: *M* = 91%, *SD* = 7.15%). The "clean" function in DataViewer (SR Research) was used to trim the data. Fixations shorter than 80 ms, and which were located within one character space of the next or previous fixation, were merged into that nearby fixation; the rest of the fixations that were shorter than 80 ms and over 1,200 ms were deleted. Trials in which the display change occurred during a fixation on the pre-boundary (pre-target) word, or when the display change was not completed until more than 10 ms after fixation onset on the post-boundary (target) word were excluded from the analyses. Finally, only trials with first pass fixations on the target word were included while those in which the pre-boundary word[5] was skipped were not included in the analyses. These procedures resulted in a final data set of 3619 fixations (81.5% of the data). These data were log transformed for analysis.

Data were analysed by means of linear mixed effects (lme) modelling using the lmer function from the lme4 package (Bates, Maechler & Dai, 2009) within the R environment for Statistical Computing (R Development Core Team, 2012) on first fixation duration, single fixation duration and gaze duration. Single fixation duration is the time that a word is fixated when it receives only one first pass fixation. First fixation duration is the duration of the initial, first-pass fixation on a word, regardless of how many fixations it receives. Gaze duration is the sum of all consecutive first pass fixations on a word before leaving the word. These are early measures of processing time on a word, reflecting lexical processing (Rayner, 1998, 2009); specifically, first fixation duration can be considered a measure of lexical access while gaze duration might also be taken to reflect text integration processes (Inhoff, 1984).

Given that this experiment did not have a perfectly balanced design (e.g., the identity condition did not form a level of either of the two independent variables), data were analysed with two lme models. We initially specified a full random structure for

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[5] The pretarget word was always a 3-7 letter word. Orthographic information can be obtained up to 6-7 letters to the right of the fixated word, so only those sentences in which the pre-target word was not skipped were included in the analyses; thus, it is likely that the initial trigram was processed parafoveally when the pre- target word was fixated.

subjects and items, to avoid being too anti-conservative (Barr, Levy, Scheepers & Tily, 2013); however, these models failed to converge. We then trimmed the random structure of the models down until they converged. In the final models, in all cases, both subjects and items were specified as random factors. In Model 1, Group (Adults vs. Children) and Condition (Identity, TL12, TL13, TL23, SL12, SL13, SL23) were specified as fixed factors, and in the Model 2, Group (Adults vs. Children), Type (TL vs. SL) and Position (12 vs. 13 vs. 23) were specified as fixed factors. The significance values and standard errors that we obtained reflect, therefore, both subject and item variability (Baayen, Davidson & Bates, 2008). Predictor variables were categorical, and were not centred. Following standard conventions, effects were considered significant when $t > 2$. In addition, confidence intervals for the model parameters were calculated using the command *confint.*

First, a lme model (Model 1) was run to examine the overall cost for children and adults associated with substituting or transposing letters in each of the positions (TL12, TL13, TL23, SL12, SL13, SL23) compared to the identity condition. The syntax for the code for this model was as follows: (lmer (ldepvar ~ Group*Condition + (1|pp) + (1|stim), data = datafile)). Next, a three-way interaction model was run with the three independent variables: Group (Adults vs. Children), Type (TL vs. SL) and Position (12 vs. 13 vs. 23) as fixed factors. The syntax for the code for this model was as follows: (lmer(ldepvar ~ Group*Type*Position + (1|pp) + (1|stim), data = datafile). We used *"contr.sdif"* (package MASS) to set up our three factors. Finally, planned contrasts were carried out on all dependent measures to examine the Transposed Letter Effect (TLE) in each position within our target words.

3.4.1. Pre-target word

First, in Model 1, for the pre-target word, only the comparison between adults and children was significant in single, first fixation and gaze duration (see Table 3.1 for coefficients, standard errors and *t*-values in Appendix A), showing that children spent more time looking at the pre-target word than adults when the identity preview was presented in the parafovea (see Table 3.2 for means and standard deviations). None of the other comparisons reached significance. This finding is consistent with other studies investigating eye movement behaviour during reading, which show that children's fixations are longer on words than adults (see Blythe & Joseph, 2011 for a review).

Table 3.2. Means (standard deviations) in milliseconds per condition in each eye movement measure in the pre-target word by adults and children.

	Adults			Children		
	SFD	FFD	GD	SFD	FFD	GD
Identity	204 (66)	205 (70)	224 (94)	269 (119)	258 (113)	332 (182)
TL12	212 (72)	211 (73)	226 (93)	278 (119)	254 (103)	320 (153)
TL13	209 (70)	206 (71)	217 (81)	259 (95)	252 (98)	306 (155)
TL23	212 (72)	211 (73)	228 (85)	281 (129)	267 (113)	352 (282)
SL12	206 (60)	208 (66)	224 (90)	246 (89)	258 (117)	322 (172)
SL13	208 (65)	204 (62)	227 (88)	256 (104)	266 (119)	334 (173)
SL23	215 (67)	210 (71)	230 (107)	284 (134)	260 (110)	329 (153)

Similarly, in Model 2, the comparison between adults and children was significant in all dependent measures, showing that children had longer fixation times on the pre-target words than adults (see 3.3 for coefficients, standard errors and *t*-values in Appendix

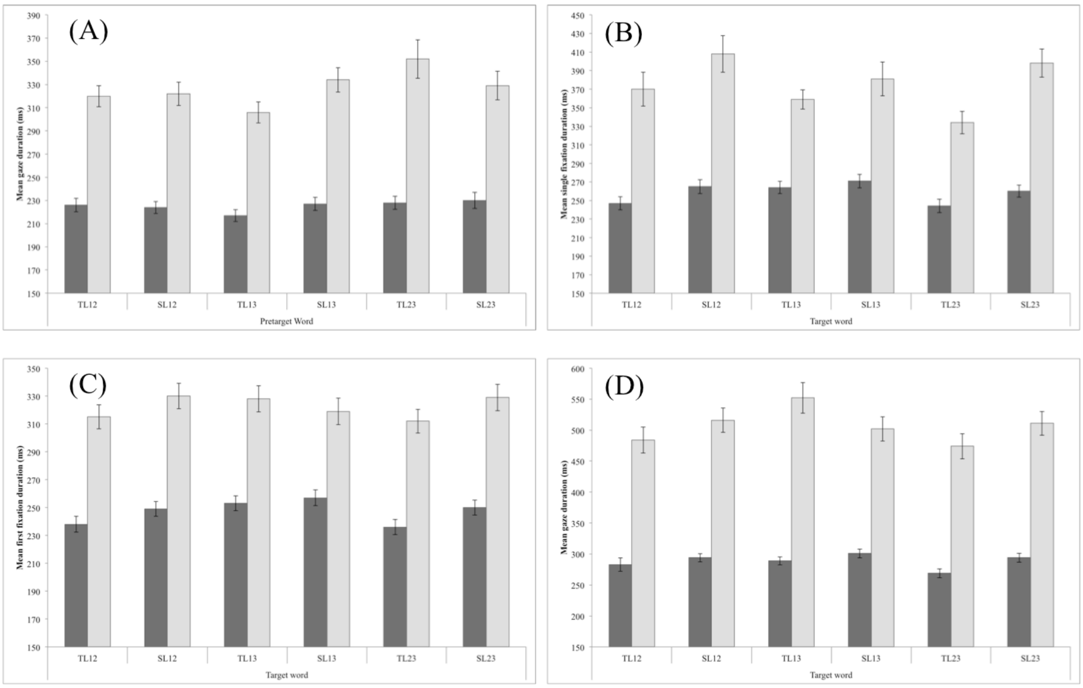
A). There was a main effect of Position for single fixation duration only, such that the pre-target word received longer reading times when 23-previews were presented in the parafovea compared to 13-previews. Extra contrasts compared 12-previews to 23-previews as a main effect, and also as an interaction with type and group. The results showed that in single fixation duration, the pre-target word received also longer reading times when 23-previews were presented in the parafovea compared to 12-previews. In addition, the interaction between Group and Position (13-23) was significant in single fixation duration: this position effect was smaller in adults (13-previews: M = 209 ms, SD = 67; 23-previews: M = 214 ms, SD = 69) compared to children (13-previews: M: 258 ms, SD = 99; 23-previews: M = 282, SD = 131).

Although this interaction was reliable, we believe that this effect should be interpreted with caution as children only made a single fixation on the pre-target word on 18% of trials, that is, a minority of trials. In addition, the interactions between Type and Position (12-13) and between Type and Position (13-23) were significant only for gaze duration. No other interactions were significant. Additional contrasts were run examining the TLE through the different positions (TL12 vs. SL12, TL13 vs. SL13 and TL23 vs. SL23) for gaze duration. Results showed a TLE in position 13 (b = -0.13, SE = 0.05, t = -2.75) such that gaze durations on the pre-target word were longer for SL13 previews compared to TL13 previews (see Figure 3.2). This effect occurred for both adults and children. Thus, at the pre-target word, there was a TLE in position 13 for both adults and children. This finding could suggest that letter position encoding was initiated earlier for TL13 previews due to its greater similarity with its base word than TL12 and TL23 previews. We make this claim based on CVC structure; TL13 previews involve the transposition of two consonants while TL12 and TL23 previews involve the transposition of a vowel and a consonant. Thus, it could be the case that consonant information is processed early when the preview and the target word are highly similar. This would support the Two-Cycles Model (Berent & Perfetti, 1995), which assumes that consonants and vowels are processed independently in two consecutives cycles. Similarly, the fact that children also showed the same TLE is congruent with previous evidence (e.g., Nazzi, 2005; Nazzi & New, 2007). Note that the difference between TL13 and SL13 is not in the structure but in the fact that TL13 keeps their letter identity, thus, this results in a TLE in position 13. These findings also suggest that both adults and children are sensitive to the orthographic structure of the parafoveal word's initial trigram (at least in relation to consonant-vowel structure) (Lee, Rayner & Pollatsek, 2001, 2002). This point will be considered further in the Discussion.

In summary, on the pre-target word, children had longer fixation times than adults in all dependent measures. Moreover, both adults and children showed a TLE in position 13 for gaze duration, such that there was a cost of 20 ms to reading the pre-target word when SL13 previews were presented in the parafovea, suggesting that both adults and children were sensitive to the initial consonant-vowel structure of the parafoveal word. We note that the effect held across both participant groups which were independent participant samples, and that there was no reliable interactive effect with group.

Figure 3.2. Reading time data for the pre-target and target words, showing the effects of Group (adults vs. children), Position (12 vs. 13 vs. 23), and Type (TL vs. SL). Pale grey bars represent data from children, and dark grey bars represent data from adults. Panel (A) shows gaze duration data on the pre-target word. Panel (B) shows single fixation duration data on the target word. Panel (C) shows first fixation duration data on the target word.

Panel (D) shows gaze duration data on the target word. Error bars represent the standard error for each condition.



3.4.2. Target word

In Model 1, similar to the pre-target word, the comparison between adults and children for the identity condition was significant in all the dependent variables (see Table 3.4 for coefficients, standard errors and *t*-values in Appendix A), showing that children spent more time looking at the target word than adults (see Table 3.5 for means and standard deviations).

T**able 3.5.** Means (standard deviations) in milliseconds per condition in each eye movement measure in the target word.

	Adults			Children		
	SFD	FFD	GD	SFD	FFD	GD
Identity	236 (73)	228 (73)	263 (107)	310 (114)	294 (147)	479 (404)
TL12	247 (88)	238 (88)	283 (171)	370 (155)	315 (142)	484 (348)

TL13	264 (80)	253 (82)	289 (101)	359 (88)	328 (158)	552 (414)
TL23	244 (86)	236 (83)	269 (113)	334 (117)	312 (144)	474 (344)
SL12	265 (90)	249 (86)	294 (104)	408 (149)	330 (154)	516 (331)
SL13	271 (85)	257 (87)	301 (109)	381 (146)	319 (157)	502 (322)
SL23	260 (76)	250 (81)	294 (109)	398 (138)	329 (161)	511 (323)

In addition, TL12 and TL23 conditions had similar viewing times to the identity condition, while all SL conditions as well as the TL13 condition produced longer viewing times than the identity condition, and this occurred for all dependent variables. This pattern strongly indicates that the TL12 and TL23 previews activated their base words as effectively as the identity preview[6]. We also obtained reliable two way interactions between group and type exclusively for single fixation durations, such that the difference in reading times between the identity and the SL12 conditions, and between the identity and SL23 conditions were greater in children (Identity-SL12: d = 90 ms; Identity- SL23: d = 80 ms) than in adults (Identity-SL12: d = 29 ms; Identity- SL23: d = 24 ms) (see Table 3.6).

In Model 2, and similar to the effects we observed for the pre-target word, the comparison between adults and children was significant in all the dependent variables (see Table 3.6 for coefficients, standard errors and *t*-values in Appendix A), showing that children spent more time looking at the target word than adults (see Table 3.5).

[6] The fact that TL12 previews showed similar viewing times to the identity condition is slightly discrepant with the results reported by Johnson *et al*. (2007), who found significant differences between the same two conditions across all dependent variables in the order of about 30 ms. There are a number of possible explanations for this discrepancy. First, looking at their set of stimuli, Johnson *et al*. did not control the initial consonant-vowel structure of the word (e.g., "acrobat", "airplane", "climate", etc.), while our stimuli share the same initial target word consonant-vowel structure. The additional variability in the Johnson et *al*. stimuli may have contributed to the lack of significance of their effect. Second, missing data and, therefore, the lack of a fully balanced experimental design alongside the use of ANOVAs may have contributed to the lack of significance (Raaijmakers, Schrijnemakers & Gremmen, 1999). Third, this discrepancy might also be explained by the fact that our fixation duration data were log-transformed while those in Johnson et al. were not.

With respect to letter position, those previews with manipulated letters in positions 13 produced longer viewing times than those with manipulated letters in position 12 (gaze duration) or in position 23 (single fixation and gaze duration) for both adults and children. This suggests that relative position information within parafoveal orthography (bigrams) facilitated word identification, as the manipulation of adjacent letters within the parafoveal word was less disruptive to lexical identification than was the manipulation of non-adjacent letters. In gaze duration, however, the interaction between group and position (13-23) was significant, indicating that the difference between 13-previews and 23-previews was greater in children than in adults.

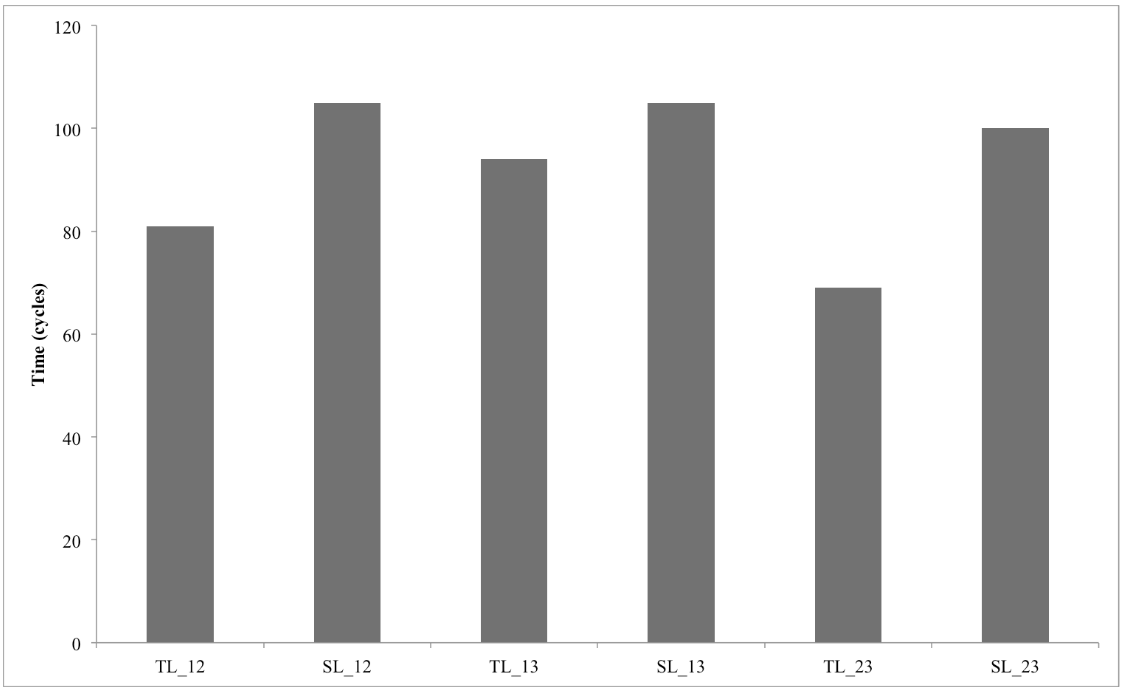
In addition, there was a significant main TLE in all the dependent measures, such that fixation times were shorter in the transposed letter conditions than the substituted letter conditions. The presence of this TLE indicated that letter position information was extracted from the parafovea independent of letter identity information, and provides evidence for parafoveal flexible letter position coding. On the assumption that it is reasonable to generalize, and assume that models of isolated word recognition might be used to generate predictions about how word identification might proceed (at least to some degree) during normal reading, then we might argue that these results provide evidence in support of models such as the Open Bigram (Grainger *et al.*, 2006), SOLAR (Davis, 1999, 2010) and SERIOL (Whitney, 2001) models (see also the Overlap model by Gómez *et al.*, 2008). Of course, we note that generalization of these findings to these models requires that they be considered in relation to processing that is distributed (spatially and temporally) across fixations. We note also that the TLE was similar for adults and children in all dependent measures. Finally, the interactions between Type and Position (12-13) and, between Type and Position (13-23) were significant for single fixation and gaze duration, and marginal for first fixation duration. No other interactions were significant.

Using planned contrasts, the TLE was examined across the different letter positions for single, first fixation and gaze durations (see Figure 3.2). There was a TLE in position 12 for single fixation and gaze durations, and in position 23 for all the dependent variables, but there was not a TLE in position 13. Again, this indicates that letter position information was extracted flexibly from the parafovea through bigrams. Again, by extension, we might argue that this result supports contextual coding models such as the Open Bigram (Grainger *et al.*, 2006) and SERIOL (Whitney, 2001) models. The 3-way interaction was not significant in Model 2 for any of the dependent measures, indicating that TLEs on the target word were comparable in children and adults. In addition, the magnitude of the TLE in position 12 (28 ms for both single fixation and 22 ms gaze duration) was smaller than that for position 23 (40 ms for single fixation duration and 31 ms for gaze duration). Again, relating our findings to models of isolated word identification, the results provide support for the SERIOL model over the Open Bigram model, suggesting that the first bigram was of greater importance than the second bigram in lexical identification.

Finally, to further evaluate our findings in terms of whether bigrams may form the basis of lexical access units, a simulation was run to examine whether the SOLAR model (Davis, 1999, 2010) might also explain the present data set. Recall that the SERIOL and the SOLAR models both use the same mechanism for the flexible encoding of letters' identities and positions (spatial coding), but differ in terms of the level of representation implemented (individual letters in the SOLAR model vs. bigrams in the SERIOL model). Critically, in the present experiment, we observed a TLE in those conditions that manipulated adjacent letters within the word (e.g., bigrams), but not in those conditions where there was an intervening letter between those that were manipulated. On the one hand, this might be explained as being due to the fact that orthographic encoding was operating at the level of the bigram (and not at the level of individual letters). If this was the case, then a simulation of our experimental manipulations within the SOLAR model should produce a different pattern of results due to that model's use of individual letter representations. Alternatively, our pattern of results might be explained as being due to an underlying spatial coding mechanism for orthographic encoding. If this latter explanation were correct, then the simulation with the SOLAR model ought to produce a similar pattern of results to that observed in the present eye movement experiment.

We used the target words from the present experiment in a simulation of a masked priming lexical decision task within the SOLAR model, implemented with the Spatial Coding Model (Davis, 2010). T-test comparisons were run to look at the TLE through the positions. Results showed that there was a TLE in position 12, 13 and 23 ($p < 0.000$). Although a TLE effect for all the positions was observed in this simulation, the effect size of the TLE varied as a function of the position: the difference between TL and SL in position 12 was of 24 ms., in position 13 was of 11 ms., and in position 23 was of 31 ms. This pattern of effects was quite similar to the pattern of effects obtained in the present eye movement experiment (see Figure 3.3), for which we found strong TLEs for conditions in which adjacent letters were manipulated. Our simulation further supports our claims that parafoveal letter position information is encoded flexibly using a spatial coding mechanism.

Figure 3.3. Output for the masked priming lexical decision task simulation run in the SCM (Davis, 2010), across the six experimental conditions.



In summary, a robust TLE was found in positions 12 for single fixations and gaze duration, and in position 23 for all dependent measures. Consistently, the comparison between the identity condition and the TL12 and TL13 conditions showed no significant differences, indicating that these TL letter strings activated the base word as effectively as the identity condition in parafoveal preview, and suggesting bigrams may be units over which orthographic information is encoded in the parafovea. On this basis it might be argued that parafoveal orthographic processing that is distributed across fixations during normal reading operates in a manner consistent with contextual coding models. However, while the TLE in position 23 was slightly greater than the effect in position 12 (supporting the SERIOL model), a simulation of the Spatial Coding Model using our target words indicated that the SOLAR model could also account for the eye movement data reported here (assuming isolated word presentation conditions). Thus, overall, we do not have conclusive evidence concerning the role of the bigram as a unit of lexical access. What we are able to conclude, however, is that our results show clearly that letter position information is encoded flexibly in the parafovea by a spatial coding mechanism in both adults and children.

3.5. Discussion

We conducted an experiment to investigate how letter position encoding occurs during lexical identification in adults and children during sentence reading. First, we discuss basic differences between adults and children in terms of their eye movement behaviour during reading, and how these behavioural changes reflect the underlying cognitive processes associated with lexical identification. Then, we will discuss the effects of our manipulations of transposed and substituted letters, considering how these effects differ between adults and children.

3.5.1. Developmental changes in lexical identification

First, as predicted, we found that children had longer reading times on both the pretarget and target words than adults. This effect was robust, occurring in single fixation durations, first fixation durations, and gaze durations. Furthermore, we found that children made more first pass fixations on these words than the adults did. This finding of more, and longer, fixations is consistent with research showing that lexical processing is, overall, slower in children compared to adults (Blythe, 2014; Blythe, Häikiö, Bertram, Liversedge, & Hyönä, 2011; Mancheva *et al.*, 2015; Reichle *et al.*, 2013; Tiffin-Richards & Schroeder, 2015; Zang, Liang, Bai, Yan & Liversedge, 2012). Such a change in lexical identification, as indexed by eye movement behaviour, may be associated with developmental changes in the quality of cognitive lexical representations as per Perfetti's Lexical Quality Hypothesis (Perfetti & Hart, 2001, 2002; Perfetti, 2007). Perfetti proposes that "high quality" lexical representations are fully specified with respect to a word's orthography (spelling), phonology (pronunciation) and semantics (meaning and grammatical class) in a "coherent" (these three constituents are available at the same time for word identification) and "reliable" manner, allowing the reader to retrieve the word very rapidly. Any representation that does not specify the information for one of these constituents is considered to be "low quality", making lexical identification relatively effortful and slow. Within this theory, it is suggested that there is a continuum on which lexical representations vary in quality as a function of the reader's knowledge about words, their vocabulary, and their reading experience. Skilled readers (for example, the adults in our sample), with many years of reading and writing experience, will have a greater number of high quality lexical representations than children who have only a few years of practice in reading and writing. Adult readers will, therefore, be more efficient in their lexical processing – the higher quality lexical representations are argued to accelerate lexical identification. This theoretical framework is consistent with our finding that children have longer reading times overall than adults.

3.5.2. Transposed letter effects in parafoveal preview

There were three key findings from the present study: (1) both adults and children were able to pre-process information regarding the identities of letters within the initial trigram of the parafoveal word; (2) there was an early transposed letter effect in positions 13 (pre-target word), such that a transposition of these letters resulted in shorter reading times than if they were substituted; (3) a slightly later transposed letter effect in positions 12 and 23 (target word). We consider each of these in turn.

Perhaps unsurprisingly, given the published body of literature, the effects showed very clearly that skilled adult readers were able to pre-process orthographic information from the parafoveal word (Binder *et al.*, 1999; Johnson & Dunne, 2012; McConkie & Zola, 1979; Rayner *et al.*, 1980). Four of the six manipulated conditions (including both transpositions and substitutions) resulted in increased reading times compared to the identity condition. This basic finding confirms that, as predicted on the basis of the published literature, skilled adult readers are pre-processing information about the identities and positions of the first three letters of the parafoveal word during silent sentence reading (we will return later to this point examining which conditions in particular increased reading times).

Relatively little is known about children's parafoveal pre-processing during reading, and how such a skill develops with age and reading skill. Importantly, some studies have indicated that the perceptual span is reduced in children compared to adults (Häikiö *et al.*, 2009; Sperlich *et al.*, 2015; Rayner, 1986). Specifically, when using the moving window technique, children aged 7-9 years old are sensitive to information presented up to 7 letter spaces to the right of fixation, in comparison to 9 letter spaces in adults. Recall that our child participants were 8-9 years old, and the pre-target words were 3-7 letters long; thus, the target word's initial trigram should always have fallen within the children's perceptual span during fixations on the pre-target word (given that participants were pre-screened to ensure they had no reading difficulties that might have resulted in a significantly smaller perceptual span). Thus, it was expected that our child participants would pre-process information from the initial trigram, and we examined specifically whether they were able to pre-process orthographic information. As predicted, we found that children were sensitive to changes in letter position information before the target word was directly fixated, demonstrating that they were pre-processing orthographic information from the parafovea as we know that adults do.

3.5.2.1.The early processing of letters 1&3

A different time course of processing was found for letters in positions 13, such that the transposed letter effect (TLE) emerged earlier for manipulations in this position compared to manipulations of letters 12 and 23. Specifically, there was a TLE for position 13 during fixations on the pre-target word, such that reading times were longer when the preview was a SL13 nonword compared to a TL13 nonword. This effect occurred for both adults and children. This very early TLE for letters 13 was not maintained during subsequent fixations on the target word.

We consider the most likely explanation to be that 13-preview manipulations involve only consonants while 12 and 23 preview manipulations involve both a consonant and a vowel. As can been seen in Appendix 1, transposing or substituting letters in position 13 created regular trigrams (e.g., *pactain-gastain* from *captain*; note that all initial trigrams had a CVC structure), while the equivalent manipulations in positions 12 and 23 (e.g., *acptain-imptain; cpatain-cgotain* respectively) were orthographically illegal (and resulted in a change to the CVC structure from the base word). It might be the case that when a parafoveal preview maintains the initial trigram's CVC structure (the TL13 and SL13 conditions), facilitated pre-processing occurs due to its orthographic and phonological regularity; this would facilitate identification of the target word once it is directly fixated (Chace *et al.*, 2005; Henderson *et al.*, 1995; Pollatsek *et al.*, 1992). In contrast, when the initial trigram is illegal (TL12, TL23, SL12 and SL23 conditions), more processing time is needed in order to extract letter identity and position information from the parafovea. Consequently, the TLEs are delayed until fixations on the target word, instead of affecting fixations on the pre-target word.

The question then remains, why this early transposed letter effect was not maintained during fixations on the target word. The Two-Cycles Model (Berent & Perfetti, 1995) proposes that phonological representations assembled during reading have an internal structure, based on the distinction between consonants and vowels. This consonant-vowel structure is argued to influence the online process of mapping each printed letter to its phoneme(s) during lexical identification. The final phonological representation of a printed word results from two independent, consecutive stages, which are associated with two distinct cognitive processes that differ in speed and automaticity. In the first stage, consonant information is encoded automatically. Then, in a second cycle, vowel information is added to the representation through a slower, less automated process. Evidence from different research areas and experimental paradigms such as speech perception (e.g., Bonatti, Peña, Nespor & Mehler, 2005), neuropsychology (e.g., Caramazza, Chialant, Capasso & Miceli, 2000) visual word recognition (Carreiras & Price, 2008; Carreiras, Duñabeitia & Molinaro, 2009; Carreiras, Vergara-Martinez & Perea, 2007, 2009; Carreiras, Gillon-Dowens, Vergara-Martinez & Perea, 2009; Grainger, Kiyonaga & Holcomb, 2006; Lee, Rayner & Pollatsek, 2001, 2002; New, Araujo & Nazzi, 2008; Perea & Lupker, 2004; Vergara-Martinez, Perea, Marin & Carreiras, 2011) and reading (Blythe *et al.*, 2014; Lee et al., 2001, 2002), have shown processing differences between vowels and consonants. For example, Carreiras, Duñabeitia *et al.* (2009) showed that primes created from a word's constituent consonants (e.g., "frl" – FAROL) evoked the same ERP waves as an identity prime (e.g., "farol"- FAROL) at early stages of processing (175-250 ms and 350-450 ms), while primes created from a word's constituent vowels (e.g. "aeo" – ACERO) evoked similar waves to unrelated primes (e.g. "iui" – ACERO), indicating that letter position assignment is modulated by the nature of the letter during the earliest phases of lexical processing (see also Carreiras, Gillon-Dowens *et al.*, 2009). More specifically, in isolated word studies, it has been shown that consonant manipulations result in a greater TLE (carema/casena- CAMARA) than vowel manipulations (cemara/cimura- CAMARA). This indicates that the identity of consonants is encoded earlier than for vowels (Carreiras *et al.*, 2007, 2009; Grainger *et al.*, 2008; Lupker, Perea & Davis, 2008; Perea & Lupker, 2004; but see also Vergara-Martinez *et al.*, 2011 for only late effects (N400) in Spanish). Similarly, Lee *et al.* (2001, 2002) showed that consonants were processed earlier and faster than vowels at initial stages of lexical identification using a delayed presentation and fast priming tasks during natural reading.

Consistently, the pattern of effects found in this experiment indicates that letter position encoding for the target word was initiated earlier (in fixations on the pre-target word) for TL13 previews (e.g. "pactain") because of their high similarity with their base word ("captain") compared to TL12 (e.g. "acptain") and TL23 previews (e.g. "cpatain"), suggesting that consonant-vowel structure was encoded very early[7]. Thus, in the specific conditions where the first letter of the word is transposed with another consonant, as in our TL13 condition, it seems that very early pre-processing letter position encoding occurs during fixations on the previous word in the sentence.

Similar to adults, children also demonstrated a TLE in position 13 during fixations on the pre-target word. This supports previous developmental evidence for a consonant-vowel asymmetry in children's lexical processing (e.g., Nazzi, 2005; Nazzi & New, 2007). The time course of this effect is striking, however. Whilst we predicted a basic TLE in children's fixation times on the target word, it is remarkable that 8-9 year old children could encode letter position information so early in lexical processing during parafoveal

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[7] This finding contrasts with the results from Johnson (2007), who showed that there were no processing differences between consonant and vowels in the parafovea during sentence reading. This could, however, be a consequence of the distance between the point of fixation on the pre-target word and the location of the manipulated letters. Specifically, Johnson's manipulations were made between letter positions 3 and 5 within the target word whilst here the manipulated letters were in positions between 1 and 3 – reduced proximity to the point of fixation.

preview, that it influenced fixation times on the pre-target word. Furthermore, this very early effect in lexical processing also seemed to have been modulated by the word's CVC structure for children in a comparable manner as was observed for the skilled adult readers.

These effects in the children's sample, indicating quite adult-like lexical processing, are most likely attributable to the fact that these children were relatively skilled readers for their age. As reported in the Methods section, our pen-and-paper assessment of reading skills confirmed that none of our participants showed any evidence of reading difficulties (which was the primary objective in conducting these additional assessments). We found, however, that the mean reading age of these children was 11.1 years (SD = 2.4) based on the wordreading subtest (it is not possible to generate an estimated reading age from the composite score). Clearly, many of the children in this sample were reading at a level higher than would be expected for their age; note that developmental changes in eye movement behaviour during reading are similar to adult's eye movement behaviour at the age of 11 years (see Blythe & Joseph, 2011 for a review).

3.5.2.2. Independent parafoveal pre-processing of letter positions and identities

Recall that four of the six manipulated conditions resulted in increased reading times compared to the identity condition, showing that information about the identities and positions of the first three letters were pre-processed in the parafovea. Critically, as predicted, reading times in the TL12 and TL23 conditions were not significantly different to reading times in the identity condition. This finding suggests that letter position information is extracted from the parafovea independently from letter identity information – in these transposed letter conditions, where all the letter identities were correct and only their positions were manipulated, there was no cost to processing. Specifically, this pattern within the data indicates that these two types of previews were activating their base words as effectively as the identity preview. This is consistent with previous evidence from isolated word recognition paradigms (e.g., Perea & Lupker, 2003b, 2004).

To confirm this, we specifically compared reading times for transposed vs. substituted letters and, as predicted, we found a robust TLE in single fixation and gaze duration. Thus, the data very clearly indicate that letter identity information is extracted from the parafovea independently from letter position information. With respect to the means by which such processing occurs, our data are suggestive of flexible letter position encoding – rather than the identified letters being rigidly assigned to a particular position, so long as the identities of the letters are correct then there is some degree of flexibility in processing where they are located within the word. This finding supports models of letter position encoding such as Overlap (Gómez *et al.*, 2008), Open Bigram (Grainger *et al.*, 2006), SOLAR (Davis, 1999, 2010) and SERIOL (Whitney, 2001). Thus, our data are also consistent with previous evidence from isolated word recognition (Grainger, 2008, for a review) and reading (e.g, Johnson *et al.*, 2007).

With respect to theoretical models of letter position encoding, some researchers have argued for encoding of individual letters whilst others have argued for encoding of pairs of letters, bigrams. Within our data, we examined whether the observed flexible letter position encoding was suggestive of either individual letters or bigrams as the unit of lexical access. Thus, we explored the TLE across the three different positions of the letters involved (12, 13, and 23), to examine whether our data were more consistent with the Open Bigram (Grainger *et al.*, 2006), SOLAR (Davis, 1999, 2010), or SERIOL (Whitney, 2001) model. These three models all assume flexible letter position encoding but, critically, they differ in terms of both (1) the unit of representation (letters vs. bigrams); and (2) the mechanism by which this information is encoded (contextual vs. spatial). Our data showed a robust TLE in position 12 for single fixation and gaze durations, and in position 23 for all dependent variables, but there was no TLE in position 13 for the target word only. First, this pattern of effects seemed consistent with use of bigrams as the unit for lexical access, thus supporting contextual coding models such as the SERIOL (Whitney, 2001) and Open Bigram models (Grainger & van Heuven, 2003; see also Grainger *et al.*, 2006). These models differ, however, in their proposed mechanism - the Open Bigram model implements a contextual mechanism for bigram encoding, while the SERIOL model assumes a spatial coding mechanism. In this latter case, an important feature of the spatial coding mechanism is that the first bigram of a word receives the most activation during lexical activation, and this decreases monotonically across the word's bigrams from left to right. Consequently, the magnitude of the TLE for position 12 should be smaller than that in position 23, and we observed exactly this pattern within our data. Thus, in addition to indicating that the readers were processing letter information within bigrams during parafoveal pre-processing, our data suggest that this processing occurred through a spatial coding mechanism, consistent with the SERIOL model.

The fact that our data were indicative of a spatial encoding mechanism led us reconsider the possibility that the SOLAR model might also explain our data. Recall that the SERIOL and SOLAR models both use the same spatial coding mechanism, but they differ in the unit of representation (bigrams vs. letters) for lexical access. The results obtained from our simulation of the Spatial Coding Model (SOLAR) were very similar to the pattern that we observed within the eye movement data. Thus, the present data set supports the conclusion that readers were using a spatial coding mechanism but it does not allow us to determine whether individual letters or bigrams are the units over which orthographic information were encoded in the parafovea.

Concerning the children's data, we found a very similar pattern to that observed in the adults' data. Specifically, children showed a benefit to reading times from having the identity preview compared to the other conditions, except for the TL12 and TL23 previews, which did not increase reading times. Thus, our data suggest that children also extracted letter position information independently from letter identity information during parafoveal pre-processing. In addition, consistent with our predictions, there was some evidence within the single fixation duration data that children exhibited proportionally greater disruption from SL12 and SL13 previews than adults. Critically, we observed a TLE for all dependent measures; however, the interaction with group was not significant, indicating that children also encoded letter position information flexibly during parafoveal pre-processing in silent sentence reading. This result is consistent with the literature from isolated word paradigms (Acha & Perea, 2008b; Castles *et al.*, 1999; 2007; Perea & Estévez, 2008).

With respect to the position of the letters manipulated, in children we observed a similar pattern of effects to adults; specifically, a robust TLE in positions 12 and 23 but not in position 13 for the target word only. This suggests that children, as well as adults, encoded letter position information early, during parafoveal processing, using a spatial coding mechanism. This is consistent with Grainger and Ziegler's model (2011), which takes into account developmental changes in letter position encoding, and assumes that skilled readers use two different sublexical codes for orthographic encoding: the coarse-grained orthographic route and the fine-grained route. Recall that these routes differ in their level of precision for letter position encoding, and in the mapping between orthography and semantics. Of relevance to the present experiment, it is in the course-grained route that letter position information is encoded in such a manner as to allow flexibility, and only through this route do readers gain an advantage from letter transpositions over substitutions (see Grainger, 2008 for a review about TLEs). Critically, it is only in the third and final proposed stage of reading development that children develop this coarse-grained route; our data suggest, therefore, that the sample of children in the present experiment must have already progressed past stages 1 and 2 (within Grainger and Ziegler's framework) in order to exhibit TLEs.

In contrast, the fact that children showed a similar TLE to adults in positions 12 and 23 is inconsistent with the study by Tiffin-Richards and Schroeder (2015), where they found minimal evidence of TLEs in their sample of 8-year-old children. There are a number of possible reasons for this discrepancy. First, through differences in the orthographic transparency of the language studied (German is a more orthographically transparent language than English). It is not clear, however, how greater orthographic transparency might result in a reduction in parafoveal pre-processing. Second, through the capitalisation of the first letter of all nouns in German (all target words were capitalised nouns in Tiffin-Richards & Schroeder's study). It seems feasible that a capitalised first letter might draw attentional resources through its saliency, facilitating lexical processing and parafoveal processing (see Rayner & Schotter, 2014). Indeed, Tiffin-Richards and Schroeder report a significant benefit from maintaining the capitalised letter in preview; however, this again would suggest that orthographic preview benefit should have been greater, not less, in the German study compared to the present data set. Finally and, in our view, most likely, these two studies differed in both the age and the reading skill of the child participants. In the present experiment, children were aged 8- to 9-years old, were in their fifth year of formal education (including Reception class), and were all relatively good readers for their age; mean reading age was 11 years. In Tiffin-Richards and Schroeder's study, children were also aged 8 years but would have only been in their third year of formal education, and their reading skills were found to be appropriate for their age. It seems likely, therefore, that the relatively greater reading skills of child participants in the present study underlies our observation of a TLE in 8-year-olds, where such effects have not previously been found.

Finally, previous evidence from children has shown that the magnitude of the TLE is greater in children than adults (e.g., Acha & Perea, 2008b; Perea & Estévez, 2008). This suggests that orthographic representations are less precisely encoded in children compared to adults (Perfetti & Hart, 2001, 2002; Perfetti, 2007), reflecting a developmental change in the tuning of the word recognition system (e.g., Castles *et al.*, 2007). Our data, however, were not consistent with this; we found no differences between our adult and child samples in terms of the magnitude of the TLE. The inconsistency between the present data set and previous studies is most likely attributable to the fact that, as previously discussed, the children who took part in the present study had a higher reading ability than expected for their age. Perhaps unsurprisingly, it is reading skill, rather than chronological age per se, which determines a reader's ability to flexibly encode letter positions within words. It is important to note, however, that we did observe group differences on overall fixations times; thus, there is clear evidence that our children were less skilled readers than the adults, but these group differences did not stem from orthographic processing. Specifically, as discussed, letter position encoding is considered a relatively early, orthographic influence on lexical processing. Our data demonstrate compellingly that any differences between the two participant groups in terms of their global eye movement behaviour during reading must reflect ongoing developmental changes in aspects of reading that occur at a higher level than orthographic encoding (Luke, Henderson & Ferreira, under revision). This is consistent with the Lexical Quality Hypothesis by Perfetti (2007; Perfetti & Hart, 2001, 2002).

3.6. Conclusions

The present data are informative with respect to how letter identity and position information is encoded during sentence reading by both adults and children. Overall, the findings reveal more fully the time course of letter position encoding as a function of the within-word location of the manipulated letters. Critically, both adults and children exhibited a similar degree and time course of orthographic processing in parafoveal preview, whereby letter position was extracted through a spatial coding mechanism. In addition, these data are also consistent with the Lexical Quality Hypothesis, indicating that age-related differences in reading times on words were a consequence of the extent to which the reader's lexical representation is fully specified (determined by reading experience, vocabulary, etc.). Further studies are needed, however, to explore the cause of these differences between adults and children, which seem related to stages of lexical processing that occur at a higher level than orthographic encoding. This study also underlies the necessity for an account of how lexical processing occurs during reading and that can be incorporated to models of eye movement control.

Finally, the limitation of this study was to not be able to test children with younger age or reading ability due to the high risk of not being able to detect parafoveal effets. Thus, in the following study we used a similar manipulation to this experiment on foveal vision rather than in parafoveal vision. Thus, possible differences in letter position encoding between adults and children would be more likely to emerge.

Chapter 4: The impact of children's reading ability on initial letter position encoding during reading

The contents of this chapter are a minor revision of Pagán, Blythe & Liversedge (under review) in the *Journal of Experimental Psychology: Learning, Memory and Cognition*[8].

4.1. Abstract

Recently, some studies with adults have shown that reading ability impacts on both the size of the perceptual span and on the extraction of parafoveal lexical information during reading (Veldre & Andrews, 2014; 2015a). Regarding children's reading, it is not clear whether differences in reading ability would affect initial-letter position encoding in lexical processing during reading. Thus, the aim of this experiment is to explore how initial-letter position information is encoded by skilled and less skilled child readers compared to adults during silent sentence reading. Four different conditions were used: control (words were correctly spelled), TL12 (letters 1&2 were transposed), TL13 (letters 1&3 were transposed) and TL23 (letters 2&3 were transposed). Results showed that TL13 condition caused the most disruption, while TL23 caused the least disruption to target-word reading for both adults and skilled child readers. Less skilled child readers, however, showed a different pattern. Although less skilled child readers showed disruption when identifying words with transposed letters, the cost did not vary systematically as a function of the letter position. These findings have important implications for letter position encoding during reading, and with respect to reading development.

[8] Experimental design, data collection, analyses and write-up were completed by Ascensión Pagán under the supervision of Hazel Blythe and Simon Liversedge.

4.2. Introduction

The aim of this study was to examine how initial letter position information within a word is encoded during foveal processing in silent sentence reading. Furthermore, we investigated the impact of reading ability on initial letter position encoding in children, particularly whether less skilled child readers encode initial letter position information differently from skilled child readers and adults.

4.2.1. Individual differences in reading

There is a large body of evidence that has investigated how certain linguistic characteristics of words can impact on eye movement behaviour during reading (see Rayner, 2009 for a review). More recently, however, interest in exploring individual differences in reading ability during reading has increased. For example, studies using the moving window paradigm have shown that although the perceptual span extends over an asymmetrical area from 3-4 character spaces to the left of the fixated word to 14-15 character spaces to the right of fixation in adults readers in alphabetic languages (McConkie & Rayner, 1975), the size of the perceptual span can vary as a function of reading ability (Ashby, Yang, Evans & Rayner, 2012; Häikiö, Bertram, Hyönä & Niemi, 2009; Veldre & Andrews, 2014), such that skilled readers have a greater perceptual span than less skilled readers. Similarly, two studies using the boundary paradigm have shown that reading ability modulates the nature and extent of information that is pre-processed from the parafovea. For instance, Chace, Rayner and Well (2005) showed that skilled adult readers used phonological codes to integrate information across saccades, while less skilled adult readers did not parafoveally pre-process this information. The authors suggested that finding that less skilled readers were not able to extract parafoveal information could be attributed to the fact that their foveal processing may be less efficient than that in skilled readers. Consistent with this idea, Veldre and Andrews (2015a) showed that highly skilled readers extracted more information from the parafovea than less skilled readers, specifically, when the fixated word was of lower frequency (high foveal load) only highly skilled readers were able to extract information from the upcoming word than less skilled readers. In addition, Veldre and Andrews (2015b) showed that, in early measures of processing, skilled adults readers had longer viewing times when the parafoveal word was a neighbour of higher frequency than the target word. In contrast, less skilled adult readers showed this inhibitory effect in later measures of processing. These studies indicate that reading ability influences the time course of lexical processing during sentence reading, affecting patterns of eye movement behaviour. Similarly, studies using natural silent reading tasks showed that slow readers had longer fixations, shorter saccades and more regressions than fast readers (Ashby, Rayner & Clifton, 2005; Haenggi & Perfetti, 1994; Jared, Levy & Rayner, 1999). In these studies, they also found that lexical frequency effects were greater for average readers than for good readers. Both groups read low frequency words more slowly than the high frequency words, but average readers needed additional time to process low frequency words. This differential pattern suggests that reading ability influences lexical processing times and, so, eye movement behaviour. In addition, slow readers relied more on phonological information for word identification during sentence reading than fast readers (Chace *et al.*, 2005); and less skilled readers relied more on context for word identification than skilled readers (Perfetti & Lesgold, 1979; Perfetti & Roth, 1981; Schwartz & Stanovich, 1981; Stanovich, 1984). All these studies show that reading ability also influences the nature of information used for lexical processing during sentence reading.

One of the difficulties of exploring individual differences in sentence reading ability is that different studies use different methods of measuring this ability. For example, some studies have focused on differences in comprehension to measure reading ability, using the Nelson-Denny Test (e.g., Ashby *et al.*, 2005; Chace *et al.*, 2005; Jared *et al.*, 1999). This test provides a global reading score based on a participant's response to 38 multiple choice questions about the contents of five texts, which vary in difficulty. As a result, this definition is limited to comprehension, and does not distinguish between other reading sub-skills such as word reading and pseudoword decoding, which could also impact on eye movement behaviour (see also Gernsbacher & Faust, 1991). In contrast, other studies have used reading speed as a measure of reading ability (e.g., Häikiö *et al.*, 2009). This approach has the limitation of assuming that fast readers are good or efficient readers. There are studies, however, showing that some fast readers have a careless reading style with a relatively low level of comprehension compared to slow readers (Hyönä, Lorch & Kaakinen, 2002; Wotschack & Kliegl, 2013). Finally, more recently, some studies have used spelling ability as a measure of the quality of a reader's orthographic representations, in order to distinguish between skilled reading in adults (e.g., Andrews & Hersch, 2010; Andrews & Lo, 2012; Hersch & Andrews, 2012; Veldre & Andrews, 2014, 2015a, 2015b). Thus, comparing studies that have defined reading ability on the basis of either comprehension, reading speed or spelling ability is difficult because the associated patterns of eye movement behaviour may correspond to different processes within reading.

The theoretical background that has been used to describe how skilled lexical processing influences skilled reading in adults comes from the Lexical Quality Hypothesis by Perfetti (2007) (see also Perfetti & Hart, 2001, 2002). In this theory, it is assumed that there is a continuum on which lexical representations vary in terms of their quality, as a function of the reader's knowledge about words, their vocabulary, and their reading and writing experience. The quality of the representations depends on how the information about a word's orthography (spelling), phonology (pronunciation) and semantic (meaning and grammatical class) is specified in the lexicon. A high quality lexical representation means that all three types of information (orthography, phonology and semantics) are well specified in the reader's mental lexicon and are available at the same time, allowing the reader to retrieve and identify this lexical representation rapidly. In contrast, a low quality lexical representation means that at least one of these types of information is either under-specified or absent, resulting in longer times to lexically identify the word, or not being able to identify the word at all. When lexical processing occurs efficiently (word identification occurs directly from orthography without phonological decoding), attentional resources are allocated for those processes that occur at a higher level than lexical processing in order to understand the meaning of a sentence or text (e.g., syntactic and semantic integration). Thus, the more high quality lexical representations a reader has, the faster and more efficiently word identification occurs, and consequently, more resources are allocated for comprehension and other higher level processes necessary for skilled reading. In other words, the more high quality representations a reader has, the more that a direct mapping from orthography to semantic information is used for lexical identification, resulting in fast and efficient lexical processing. In contrast, the fewer high quality representations a reader has, then the more they depend on an indirect mapping from orthography to meaning, via phonological information, for lexical identification, resulting in slow lexical processing (see e.g. The Dual Route Cascaded Model by Coltheart, Rastle, Perry, Ziegler & Langdon, 2001). This theoretical approach has been supported by recent empirical evidence from eye movement research. These studies have shown that readers with high quality lexical representations had larger perceptual span (Veldre & Andrews, 2014) and exhibited greater parafoveal preview benefit (Veldre & Andrews, 2015a) than readers with low quality lexical representations. Similarly, readers with high quality lexical representations showed interference from orthographically related previews (e.g., smile-slime), while readers with low quality lexical representations showed facilitation from the same type of previews (Veldre & Andrews, 2015b). Similarly, Luke, Henderson and

Ferreira (2015) investigated whether the quality of lexical representations influenced eye movement behaviour in adolescents aged 11-13 years old during normal text reading. They found that adolescents with high quality lexical representations (inferred from their reading ability) exhibited more adult-like reading behaviour, with shorter gaze durations and fewer refixations, than adolescents with low quality lexical representations. This supports the idea that the quality of lexical representations stored in the reader's mental lexicon influences reading ability, causing a different pattern of eye movement behaviour.

Most evidence mentioned above concerning individual differences in reading comes from studies with adults, showing that reading ability impacts on eye movement behaviour. Until now, however, there have been no studies investigating the influence of reading ability on eye movement behaviour in English children as they read sentences. In this study, we investigated whether reading ability influences children's eye movement behaviour during English sentence reading. We recruited three groups of participants: adults, skilled, and less skilled child readers. In this study, adults were considered as the baseline (efficient reading), presumed to have more high quality lexical representations due to more years' experience of reading and writing than children. The interesting comparison here is between skilled and less skilled children who had the same number of years' experience of reading and writing, but whom we anticipated would differ in their number of high quality representations. We used the Wechsler Individual Achievement Test II (WIAT-II; Wechsler, 2005) to assess word reading, pseudoword decoding and comprehension in all our participants, making sure that they did not have any reading difficulties, and to distinguish between skilled and less skilled child readers (see Method section). We predicted overall differences in reading times on words between skilled and less skilled child readers of the same age, on the basis that those two groups should vary in the quality of their lexical representations. Whilst previous research has demonstrated age-related decreases in reading times on words, and these decreases have been attributed to improvements in the speed of lexical processing (e.g., Blythe, 2014; Blythe & Joseph, 2011; Reichle *et al.*, 2013), to date, no theoretical explanation for this developmental change has been articulated. Consistent with Luke *et al.* (2015), we suggest that the number of high quality lexical representations that a reader has in their mental lexicon may be a key determinant of the speed of lexical processing as indexed by their eye movement behaviour. According to the Lexical Quality Hypothesis, adults should show the shortest reading times overall, relative to both skilled and less skilled child readers. Also, skilled child readers should show shorter reading times overall than less skilled child readers. In contrast, if the quality of lexical representations does not influence eye movement behaviour, then no differences in reading times should be observed between skilled and less skilled child readers.

4.2.2. Letter Position Encoding

Another aim of this study is to investigate whether reading ability modulates how letter position information is encoded in children. Recent evidence from both isolated word and silent sentence reading paradigms suggests that letter position information is encoded independently from letter identity information in a flexible manner in both adults and children (e.g., see Grainger, 2008; Frost, 2012, for reviews). As a consequence, new models of letter position encoding have been developed to account for this flexible letter position encoding 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, Ratcliff & Perea, 2008); and the SERIOL model (Whitney, 2001).

Only one study, however, has investigated the influence of reading ability on letter position encoding in English adults. Andrews and Lo (2012) explored whether the quality of the lexical representations stored in a reader's lexicon, as assessed with a spelling test, influenced lexical processing in a masked priming lexical decision task. When target words (e.g. *clam*) were primed by their neighbours (e.g. *calm*), readers with high quality lexical representations took longer to identify the target word (*clam*) than readers with low quality representations. In addition, when target words (e.g., *judge*) were primed by transposed letter nonwords (e.g., *jugde*), readers with high quality lexical representations were faster to identify the word (*judge*) than readers with low quality lexical representations. This pattern of findings suggests that readers with high quality lexical representations were able to encode letter position information more flexibly than less skilled adult readers, resulting in stronger facilitatory transposed letter effects. Second, lexical representations in skilled readers were more precisely encoded than less skilled readers, resulting in more lexical competition from similar words, showing stronger inhibitory neighbour effects (see also Andrews & Hersch, 2010 for similar evidence with substitution neighbours).

It seems contradictory to argue that if lexical representations are precisely encoded, then readers are using a flexible letter position encoding mechanism for lexical identification. Note that the lexical quality hypothesis requires encoding precise orthographic information (letter identity and order) for efficient lexical processing. In contrast, models that propose flexible letter position encoding require letter identity information to be encoded independently from letter position information, resulting in successful lexical identification even though the orthographic input does not fully match the stored orthographic representation. Recall, however, that letter position encoding occurs at an early stage of lexical processing, that is, it is a pre-lexical process, while subsequent lexical identification is influenced by the characteristics of other words stored in the lexicon. Thus, it seems feasible that flexible letter position encoding occurs pre-lexically, facilitating access to lexical representations that are precisely encoded. In other words, the partial information that comes from a transposed letter input (e.g. *jugde*) would activate the base word (*judge*) strongly if the reader had the base word precisely represented, resulting in the robust facilitatory transposed letter effects found in the literature (e.g., Johnson, Perea & Rayner, 2007; Pagán, Blythe & Liversedge, 2015). If the reader has two high quality lexical representations that share the same letter identities but vary in letter position (e.g. *smile* and *slime*), the use of flexible letter position encoding will result in strong inhibitory effects such as longer times to retrieve the correct candidate (lexical competition) or misidentifications of the correct candidate (e.g., Acha & Perea, 2008; Andrews & Lo, 2012; Johnson, 2009; Pagán, Paterson, Blythe & Liversedge, 2015).

Regarding how letter position information is encoded by children, some studies have been carried out using either isolated word (Acha & Perea, 2008, Castles, Davis & Forster, 2003; Castles, Davis & Letcher, 1999; Castles, Davis, Cavalot & Forster, 2007; Friedman, Dotan & Rahamim, 2010; Grainger, Lété, Bertand, Dufau & Ziegler, 2012; Kohnen& Castles, 2013; Kohnen, Nickels, Castles, Friedman & McArthur, 2012; Lété & Fayol, 2013; Paterson, Read, McGowan & Jordan, 2015; Perea & Estévez, 2008; Ziegler, Bertand, Lété & Grainger, 2012) or sentence reading (Pagán, Blythe & Liversedge, 2015; Tiffin-Richards & Schroeder, 2015) paradigms. Although none of these studies have explored the influence of reading ability on letter position encoding in children, they showed that 7-9 year old children encoded letter position information flexibly, as adults do. Critically, in some studies, the only difference found was that the magnitude of the effects was greater for 7-9 year old children compared to 10-11 year old children or adults (e.g., Acha & Perea, 2008; Castles *et al.*, 1999, 2007; Perea & Estévez, 2008). This difference in the size of the effects was attributed to the fact that lexical representations are less precisely encoded in children than adults, as a result of the change in the tuning of the word recognition system. The lexical tuning hypothesis (Castles *et al.*, 2007) suggests that beginning readers, who know a relatively small number of words, encode only approximate information about letter position (flexible letter position encoding), resulting in a successful identification of the word even though there is not a full overlap between the orthographic representation and the visual input string. When readers increase the size of their vocabulary, the lexical identification system became more precise in order to distinguish between orthographically similar words, resulting in less flexible letter position encoding.

Grainger and Ziegler's model (2011) is a developmental multiple-route model of how children learn to read words (see Grainger *et al.*, 2012), very similar to dual-route models of isolated word recognition (e.g., Coltheart *et al.*, 2001). In this model, there are two routes: the phonological (indirect) and orthographic (direct) routes. The phonological route, which in terms of learning to read, precedes the orthographic route, is not directly specified in the model, but it assumes that letters are processed serially within a word through overt phonological recoding to access semantics. The orthographic, or direct route, directly maps the orthography to semantic representations. In this model, there are two orthographic routes: the fine-grained route and the coarse-grained route. The orthographic coding involved in these two routes is fundamentally different, and depends on the level of precision of letter position encoding. The fine-grained route refers to the mapping of orthography onto sublexical morphological and phonological representations, which are already stored in the lexicon, to retrieve the meaning of the specific word. In this route, there is no flexibility of letter position encoding because the encoding of specific letter position information for contiguous, multi-letter graphemes (e.g., sh, th, ph) and morphemes (e.g., ing, er, re) is required to identify words. The relevance of this route is supported by studies using isolated word paradigms such as the pseudo-homophone advantage (Rastle & Brysbaert, 2006) and morphological priming (Rastle & Davis, 2008); and by reading studies that showed parafoveal pre-processing of phonological information (e.g., Henderson, Dixon, Petersen, Twilley & Ferreira, 1995; Lima & Inhoff, 1985; Miellet & Sparrow, 2004), reflecting fast access to phonological information once a pronounceable string of letters is presented. The coarse-grained route refers to the direct mapping from orthography to semantic representations. In this route, both contiguous and non-contiguous pairs of letters (open-bigrams) are used to facilitate word identification, using flexible letter position encoding. As a consequence, the system uses the most visible letters (in terms of retinotopic position) to select the group of letters that are most informative to facilitate the identification of words. The relevance of this route in lexical identification is supported by studies that show transposed letter effects, and which indicate flexible letter position encoding (see Grainger, 2008; Frost, 2012 for reviews).

In this model, three broad phases of lexical identification were proposed to describe developmental changes in letter position encoding and, consequently, in the use of each route. The first phase, that is considered as a necessary precursor but is not directly specified within the model, assumes that letters are processed serially within a word through phonological recoding. From this effortful, serial procedure, in the second phase, orthographic encoding of letters occurs in parallel due to the development of position-specific letter detectors. Finally, in the third phase, the development of parallel, independent letter processing causes the development of two complementary routes for orthographic encoding, forming the basis of skilled silent word reading.

More recently, some studies that based their predictions on Grainger and Ziegler's model (2011), have demonstrated that flexible letter position encoding occurs when lexical representations are encoded more precisely, specifically, after Grade 2 (e.g., Grainger &

Ziegler, 2011; Grainger *et al.*, 2012; Lété & Fayol, 2013; Ziegler *et al.*, 2014). Thus, in this study, we explored whether children's reading ability influences the nature of orthographic encoding used for lexical identification as they read words with transposed letters embedded in sentence contexts. Recall that we predicted overall group differences (adults vs. skilled vs. less skilled children) on the basis of the Lexical Quality Hypothesis. This model, however, does not account for letter position encoding during lexical identification. Furthermore, whilst Grainger and Ziegler's model explicitly incorporates developmental change during lexical processing, it is also somewhat limited with respect to developmental changes in letter position encoding. Specifically, as described above, the model defines three phases: (1) very early reading (overt, serial decoding); (2) early parallel processing of the letters within a word; leading to (3) the use of both a fine-grained and a coarse-grained route for parallel orthographic encoding. Critically, flexible letter position encoding (the mechanism by which a reader is able to activate the correct lexical entry from a transposed letter input) is only achievable through the coarse-grained route in Phase 3. Once a reader has established these two routes for orthographic encoding, the model does not explicitly articulate any further developmental change. There is, however, a growing body of experimental evidence demonstrating age-related changes in flexible letter position encoding in children (e.g., Grainger & Ziegler, 2011; Grainger *et al.*, 2012; Lété & Fayol, 2013; Ziegler *et al.*, 2014).

4.2.3. Initial versus Internal Letters

Another aim of this study was to explore whether reading ability influenced how initial letter information was encoded during sentence reading. The importance of initial letter identity and position information has been demonstrated in skilled adult reading using a variety of manipulations such as letter degradation (e.g., Jordan, Thomas, Patching & Scott-Brown, 2003) and letter transposition (e.g., Rayner, White, Johnson & Liversedge, 2006; White, Johnson, Liversedge & Rayner, 2008; see also Wang *et al.*, 2013; Yan *et al.*, 2012 for evidence from stroke deletion manipulation in Chinese). These studies, where all the words in the text were manipulated, showed that the degradation or transposition of a word's initial letter caused more cost to reading (longer reading times) than internal letter degradation or transposition, indicating the elevated status of word-initial letters for lexical identification during sentence reading. These studies also support the idea that internal letter position information is encoded more flexibly than initial letter information because of the importance of the initial letter as a lexical access unit for word identification during sentence reading (see Briihl & Inhoff, 1995; Chapter 3 of this thesis; Gagl, Hawelka, Richlan, Schuster & Hutzler, 2014; Jonhson, 2007; Johnson & Dunne, 2012; Johnson & Eisler, 2012; Johnson *et al.*, 2007; Jordan *et al.*, 2003; Pagán, Blythe & Liversedge, 2015; Plummer & Rayner, 2012; Rayner, McConkie & Zola, 1980; Tiffin-Richards & Schroeder, 2015).

This evidence is consistent with new models of letter position encoding (the SOLAR model, Davis, 1999, 2010; the Open Bigram model, Grainger & van Heuven, 2003; Grainger *et al.*, 2006; Grainger & Ziegler, 2011; the Overlap model, Gómez *et al.*, 2008; and the SERIOL model, Whitney, 2001), which account for flexible letter position encoding. They predict different mechanisms to encode letter position information for internal and initial letters. They assume that internal letter position information is encoded independently from letter identity information, using a flexible letter position encoding mechanism. In contrast, initial letter position information is encoded jointly with letter identity information, using a strict letter position encoding mechanism.

Although some studies have been carried out to explore the role of initial versus internal letter encoding in children during sentence reading (Pagán, Blythe & Liversedge, 2015; Tiffin-Richards & Schroeder, 2015), there is only one study that investigated whether children's reading ability influenced the cost to reading a word as a function of the location of the letters that were manipulated. Rayner and Kaiser (1975) recruited 6th grade readers who were very good readers, and 12th grade readers who were poor readers (they read at a similar level to children in the fourth grade), for a reading aloud task. They found that texts with initial, visually dissimilar substituted letters (e.g., *yorld*) had a greater cost to reading than texts with middle or final dissimilar substituted letters (e.g., *wogld* or *worlr*) for both groups of children, indicating that initial letters are also very important for lexical identification in children during text reading due to its special role as a lexical access unit (as per Pagán, Blythe & Liversedge, 2015). In addition, they found that although poor readers took more time than good readers to identify the words, letter position information was encoded similarly in both groups of children.

Until now, there have been no studies, however, that have explored the cost of reading words with transposed letters in skilled relative to less skilled child readers during silent sentence reading. In this study, we examined the effects of the following manipulations to determine in each case whether or not it was modulated by reading skill: (1) whether a word's initial letters are encoded less flexibly than internal letters; (2) whether such processing operates over individual letters, or over adjacent pairs of letters, such that either the first letter or the first bigram of a word is crucial for the identification of that word due to its role as an access unit; and (3) whether such processing is modulated by children's reading ability.

In order to examine these issues, we used a silent sentence reading task, and the type of target word was manipulated with four different conditions: control (no letter manipulation); letters 1&2 transposed (TL12); letters 1&3 transposed (TL13); and letters 2&3 transposed (TL23). We predicted that the control condition would receive the shortest reading times (e.g. Rayner *et al.*, 2006; White *et al.*, 2008). In addition, two alternative patterns of effects were predicted with respect to the transposed letter conditions. In one case, the greatest cost to reading was predicted to occur when the first letter was manipulated (TL12 and TL13), while TL23 would cause less disruption to reading, indicating more flexible letter position encoding for internal letters than when the first letter is involved. Alternatively, the TL13 would be predicted to cause the most cost to reading, while the TL12 and TL23 manipulations would cause less disruption to reading, indicating that adjacent letters are encoded more flexibly than non-adjacent letters (as per in Chapter 3 of this thesis; Pagán, Blythe & Liversedge, 2015). Critically, we examined whether such effects might be modulated by the age and/or skill of the reader.

4.3. Method

4.3.1. Participants

A total of 72 participants (24 adults and 48 children) took part in this experiment. The children were recruited from Years 3 and 4 of primary schools in and near Southampton, and had a mean age of 9 years (range = 7.11 – 9.9, *SD* = 0.6). The adult participants were from the University of Southampton, and had a mean age of 20 years (range = 18-27, SD = 2.0). All participants had normal or corrected to normal vision, and were native speakers of English with no known reading difficulties. Furthermore, pre-screening with the WORD subtest of the Wechsler Individual Achievement Test II (WIAT-II; Wechsler, 2005)[9] confirmed that no participants showed evidence of reading difficulties. In addition, this assessment allowed us to classify the children into skilled and less skilled readers using the standardized scores in word reading, pseudoword decoding,

[9] Although the WIAT-II is not a direct test of the quality lexical representation, I chose this test because it is standardized test and gives a good measure of children's reading ability. As a consequence, we can infer the quality of the lexical represetnations,using a similar principle as in other studies (e.g., Luke et al., 2015). Future research will consider to use a spelling test as a direct measure of lexical quality (Hersch & Andrews, 2010).

and comprehension (see Table 4.1). The two groups of children were matched for years of literacy instruction (Skilled: M = 3.5; Less Skilled: M =3.7, p = 0.2). They were unaware of the purpose of the experiment until afterwards. University students received course credits as a reward for participating.

Table 4.1. Means (Standard deviations) of the standardized scores of the WORD subtests of the WIAT-II (Wechsler, 2005) for adults, skilled and less skilled child readers. The three groups of readers differ significantly in all the reading variables (*p'*s < .02). The only exception was between adults and skilled child readers who showed similar word reading scores (*p* > .20).

	Adults	Skilled children	Less skilled children
WIAT-II	M (SD)	M (SD)	M (SD)
Age (years)	20 (2)	8.9 (0.6)	8.9 (0.6)
Word	113 (5)	111 (8)	97 (7)
Pseudoword	113 (3)	116 (3)	103 (4)
Comprehension	112 (9)	108 (8)	98 (6)
Composite	115 (6)	113 (7)	97 (4)

4.3.2. Apparatus

The sentences were presented on a 21" CRT monitor, with a refresh rate of 100 Hz and a resolution of 1024 x 768, interfaced with a PC at a viewing distance of 60 cm. Sentences were presented in black, Courier New, size 12 font on a grey background; three characters subtended 1° of visual angle. Although reading was binocular, eye movements were recorded only from the right eye, using an EyeLink 1000 tracker (S.R. Research Ltd.), with forehead and chin rests in order to minimize head movements. The spatial resolution of the eye tracker was 0.05°, and the sampling rate was 2000 Hz.

Word reading, pseudoword decoding and reading comprehension for each participant were assessed using the WIAT-II (Wechsler, 2005).

4.3.3. Material and design

Fifty-six experimental sentences containing a 6-7 letter target word were selected. Target words (nouns or adjectives) were bisyllabic with a CVC structure for the initial trigram, which was within the same syllabic unit (e.g., *bandage*). These target words had fewer than three orthographic neighbours, and had a mean Age of Acquisition of 6.78 years (*SD* = 1.70) (Kuperman, Stadthagen-Gonzalez & Brysbaert, 2012). Target word frequency was in a range between three and 276 per million using child frequency counts (*M* = 37, *SD* = 53) (Children's Printed Word Database; Masterson, Dixon & Stuart, 2003) and in a range between 0.61 and 3483 per million using adult frequency counts (*M* = 179, *SD* = 559) (English Lexicon Project Database; HAL corpus, Balota *et al.*, 2007).

Four different conditions were generated for each target word. A control condition, in which the target word was spelled correctly (e.g. *bandage*), a nonword with the first and the second letters transposed (TL12, e.g., *abndage*), a nonword with the first and the third letters transposed (TL13, e.g., *nabdage*), and a nonword with the second and the third letters transposed (TL23, e.g., *bnadage*). None of the target transpositions produced real words, and all of the transpositions produced a change in spelling. In addition, for each sentence, all words which had five or more letters were manipulated by transposing the letters according to each condition, in order to reduce the salience of the target word within the sentence (e.g., Control: *"The nurse had to put a fresh <u>bandage</u> on his leg after three weeks"*; TL12: "*The unrse had to put a rfesh <u>abndage</u> on his leg fater htree eweks*"; TL13: "*The runse had to put a erfsh <u>nabdage</u> on his leg tfaer rhtee eewks*"; and TL23: "*The nruse had to put a fersh <u>bnadage</u> on his leg atfer trhee weeks.*").

In addition, we created two types of questions. First, Yes/No comprehension questions were included after half of the experimental sentences to ensure that readers understood the meaning of the sentences presented. Second, target word questions were included after a different 25% of sentences, to ensure that readers were correctly identifying the target nonwords in the text. We created 54 pairs of words matched by length: each pair was comprised of the correct target word that had appeared in the sentence, and a distractor word (e.g., *bandage* and *baggage*). The distractor word was created from the correct word by changing between one and four letters. This resulted in two pairs with one letter different, 30 pairs with two letters different, 19 pairs with three letters different and three pairs with four letters different. The pair of words was presented in the centre of the screen and the participants had to indicate which of the two words had appeared (albeit in a misspelled format) in the sentence that they had just read.

The 56 experimental sentences were counterbalanced across four lists using a Latin Square design. Each list was read by 18 participants (six adults, six skilled children and six less skilled children). Each list included 4 practice sentences, and 56 experimental sentences (14 per condition). The sentences occupied one line on the screen (maximum = 60 characters; M = 58 characters), and the target nonword always appeared in the middle of the sentence. The experimental sentences were presented in a random order to each participant.

4.3.4.Procedure

The three reading subtests- word reading, pseudoword decoding and comprehension- of the WIAT-II were completed first, to confirm that our participants had no reading difficulties, and to classify the children as skilled or less skilled readers, then, the eye movement experiment was conducted. Participants were told that some of the letters in some of the words could be mixed up and, that he/she should be able to determine the meaning of those words. Thus, they should focus on reading each sentence for comprehension. After each sentence, the participant had to press a button on the game controller to continue and, following 50% of the sentences, to answer Yes/No to comprehension questions. In addition, following 25% of the sentences, the participant had to answer a two- choice question about the target word in order to assess that they could identify correctly the target word. Participants were free to take a break whenever they wished, and could withdraw from the experiment at any point. The experiment lasted about 50 minutes.

4.3.5. Data analysis

Participants that scored less than 65% on either the comprehension or the target word questions were removed from the analyses (a total of six participants were removed). The 24 adult participants scored an average of 97% (SD = 4.4) on the comprehension questions and all of them scored 100% in the target questions. The 23 skilled child participants scored an average of 87% (SD = 7.7) on the comprehension questions and an average of 97% (SD = 6.9) in the target questions. The 19 less skilled child participants scored an average of 78.4 (SD = 8.6) on the comprehension questions and an average of 97% (SD = 7.0) in the target questions. The three groups of participants differed significantly in comprehension accuracy (ps< 0.00). In target accuracy, however, adults differed significantly from both types of groups (ps < 0.04), while both skilled and less skilled child readers did not (p > 0.7).

The "clean" function in DataViewer (SR Research) was used to trim the data. Fixations shorter than 80 ms, and which were located within one character space of the next or previous fixation, were merged into that nearby fixation; the rest of the fixations that were shorter than 80 ms and over 1200 ms were deleted. In addition, fixations more than 2.5 standard deviations from each participant per condition's mean were considered as outliers (less than 3%). The data were log transformed for analyses. The final dataset contained 4030 fixations for global analyses and 3629 fixations for local analyses. See below.

A range of standard eye movement measures was computed for global and local analyses (Rayner, 2009). For global analyses, mean fixation duration (the mean duration of all fixations in the sentence), mean progressive saccade amplitude, mean sentence reading time, and the mean total number of fixations per sentence were included. For local analyses of the target word, single fixation duration (the time for which a word was fixated when it received only one first pass fixation), first fixation duration (the duration of the initial, first-pass fixation on a word, regardless of how many fixations it received) and gaze duration (the sum of all consecutive fixations on a word before leaving the word) were included.

Data were analysed by means of linear mixed effects (lme) modelling using the lmer function from the lme4 package (Bates, Maechler & Bolker, 2012) within R (R Development Core Team, 2013). For all the analyses, Group (Adults, Skilled Children, Less Skilled children) and Type (Control, TL12, TL13 and TL23) variables were specified as fixed factors. We initially specified a full random structure for subjects and items, to avoid being anti-conservative (Barr, Levy, Scheepers & Tily, 2013); however, this model failed to converge. We then trimmed the random structure of the model down until it converged. In the final model, in all cases, both participants and items were specified as random factors. Significance values and standard errors reflect, therefore, both participant and item variability (Baayen, Davidson & Bates, 2008). Predictor variables were categorical, and were not centered. Following standard conventions, effects were considered significant when *t* >2. Also, the fixed factors were specified using "contr.sdif" (MASS), so the intercept was the Grand Mean. The contrast were run also using planned comparisons. In addition, confidence intervals for the model parameters were calculated using the command *confint.* The syntax for the code for the lme model was as follows: (lmer (ldepvar ~ Group*Type + (1|pp) + (1|items), data = datafile). Additional contrasts were carried out to compare adults and less skilled child readers, as well as identity and TL13 conditions; identity and TL23 conditions; and TL12 and TL23 conditions for single, first fixation, gaze duration and total time.

4.4. Results

4.4.1. Global analyses

Global analyses were carried out to examine differences between our three groups of participants in their eye movement behaviour. Note that the transposed letter manipulation was well controlled for the target word/nonword, but not for the other words that were manipulated in the sentence. Thus, we did not explore transposition effects in these analyses.

Adults had shorter fixation durations (b = 0.23, SE = 0.03, t = 7.3), longer progressive saccade amplitudes (b = -0.28, SE = 0.10, t = -2.7), shorter reading times (b = 0.53, SE = 0.08, t = 6.9), and made fewer fixations on the sentence than skilled child readers (b = 7.11, SE = 1.50, t = 5.1) (see Table 4.2 for means and standard deviations). This finding is consistent with previous studies investigating children's eye movement behaviour during reading (Blythe, Häikiö, Bertram, Liversedge, & Hyönä, 2011; Blythe *et al.*, 2006; Blythe, Liversedge, Joseph, White, & Rayner, 2009; Häikiö *et al.*, 2009; Häikiö, Bertram & Hyönä, 2010; Huestegge, Radach, Corbic & Huestegge, 2009; Joseph, Liversedge, Blythe, White, & Rayner, 2009; McConkie *et al.*, 1991; Rayner, 1986; Tiffin-Richards & Schroeder, 2015).

Adults had shorter fixation durations (*b* = -0.33, *SE* = 0.04, *t* = -9.2), longer progressive saccade amplitudes (*b* = 0.34, *SE* = 0.10, *t* = 3.3), shorter reading times (*b* = 0.60, *SE* = 0.09, *t* = 6.9), and made fewer fixations in the sentence than less skilled child readers (*b* = -7.34, *SE* = 1.55, *t* = -4.7) (see Table 4.2).

Table 4.2. Descriptive Means (Standard Deviations) for each participant group in each dependent measures on the sentence.

	Fixation Duration (ms.)	Progressive Saccade Amplitude (deg.)	Sentence reading time (ms.)	Number of fixations
Adults	249 (49)	1.5 (0.9)	5291 (2181)	14 (6)
Skilled Children	314 (51)	1.2 (0.9)	9142 (3957)	21 (8)
Less Skilled Children	342 (58)	1.1 (0.9)	9815 (4450)	21 (9)

Finally, the comparison between skilled and less skilled child readers was only significant in average fixation duration ($b = 0.08$, $SE = 0.03$, $t = 2.5$), indicating that skilled child readers had shorter fixation durations than less skilled child readers (see Table 4.2). No differences were found between skilled and less skilled children in progressive saccade amplitude, sentence reading time, or total number of fixations (ts < 0.7). This is consistent with previous studies, which compared children in different age groups (e.g., Häikiö *et al.*, 2009), but it is the first demonstration that reading ability in children with similar ages modulates fixation duration during sentence reading. We return to this point in the Discussion.

To sum up, adults had shorter fixation durations, longer progressive saccade amplitudes, shorter reading times and made fewer fixations during reading than both skilled and less skilled child readers. Skilled and less skilled child readers only differed in mean fixation duration, such that less skilled child readers had longer fixations times than skilled child readers.

4.4.2. Local analyses

4.4.2.1. Overall differences between the three groups of participants

Firstly, the lme model showed that the comparisons between adults and skilled child readers were significant for all dependent measures (see Table 4.3 for coefficients, standard errors and t-values in Appendix A), showing that adults had shorter viewing times on the target nonwords than skilled child readers (see Table 4.4 for means and standard deviations). The comparisons between skilled and less skilled child readers were significant only for single fixation and gaze duration, indicating that skilled child readers had shorter fixation times on the target word/nonword than less skilled child readers. Furthermore, the contrasts between adults and less skilled child readers were significant for all dependent variables, indicating that less skilled child readers had longer viewing times on the target word/nonword than adults. As predicted, this pattern suggests that adults were able to retrieve and identify the correct entry in their mental lexicon faster than both skilled and less skilled child readers. Similarly, skilled child readers were able to retrieve and identify the correct word faster than less skilled child readers. This differential pattern could be attributed to differences in the precision of the lexical representations (inferred from the differences in reading ability) that are activated by the misspelled word (as in the Lexical Quality Hypothesis by Perfetti, 2007).

Table 4.4. Descriptive Means (Standard Deviations) for each participant group in the four experimental conditions in each dependent measures on the target word.

		First Fixation Duration	Single Fixation Duration	Gaze Duration
Adults	Identity	213 (68)	223 (78)	249 (98)
	TL12	258 (118)	284 (137)	358 (208)
	TL13	287 (147)	339 (172)	462 (317)
	TL23	242 (86)	263 (109)	315 (157)
Skilled Children	Identity	307 (141)	348 (154)	465 (252)
	TL12	353 (208)	434 (191)	795 (612)
	TL13	358 (208)	462 (182)	894 (761)
	TL23	343 (187)	401 (196)	638 (460)
Less Skilled Children	Identity	358 (158)	445 (163)	628 (428)
	TL12	376 (241)	495 (266)	781 (631)
	TL13	360 (205)	473 (205)	925 (764)
	TL23	373 (207)	458 (165)	891 (847)

4.4.2.2. The cost of processing misspelled words

The control condition elicited shorter fixation durations than either the TL12 or TL13 conditions in all dependent measures, while the control condition elicited shorter viewing times than the TL23 condition for gaze duration only. This suggests that when the first letter was transposed, lexical identification was disrupted; when only internal letters were transposed, the TL23 nonword activated the base word representation in the mental lexicon similarly to the correctly spelled word in early measures of processing (single fixation and first fixation durations), reflecting pre-lexical processing and indicating rapid activation of the correct entry in the mental lexicon. Later in processing (gaze duration), after lexical identification occurred, however, TL23 condition caused longer fixation times than the control condition, indicating that readers may have been aware of the misspelled words. This pattern of effects was consistent with previous studies, showing that although words with transposed letters caused disruption to reading compared to correctly spelled words, internal letter transpositions were the easiest to read (e.g. Rayner *et al.*, 2008; White *et al.*, 2008)

There were no significant interactions with Group (Adults-Skilled Child) when comparing the control conditions with the other experimental conditions in single fixation or gaze duration. There was, however, an interaction between Group (Adults-Skilled Child) and Type (Control-TL13) in first fixation duration, such that the difference between the control and the TL13 conditions was greater for adults than skilled child readers. This interaction might be due to the difference in the percentage of first pass fixations that adults and skilled child readers made. Note that the pattern between these two groups did not differ either in single fixation or gaze duration; thus, the cost of processing misspelled words in both adults and skilled children was very similar overall.

When comparing skilled with less skilled child readers, two interactions yielded significant effects. First, the interaction with Type (Control-TL13) was reliable in single fixation duration and gaze duration. The differences between the correctly spelled words and the TL13 nonwords were smaller for less skilled than skilled child readers. Second, the interaction with Type (Control-TL12) was reliable in gaze duration, showing that the difference between correctly spelled words and the TL12 nonwords was smaller for less skilled than skilled child readers in gaze duration. These results indicate that although less skilled child readers also showed disruption to lexical processing when there was a transposition compared to the correctly spelled words, that cost was more pronounced in skilled than less skilled child readers when the first letter was manipulated (TL12 and TL13). This pattern was unexpected; one might have expected that the cost of processing misspelled words would be more pronounced in less skilled than skilled child readers. This may be due to the nature of lexical processing in each of these groups. Specifically, less skilled child readers may be using a mechanism that activates phonological codes to process both words and nonwords due to the fact that their lexical processing is not as efficient as that of skilled child readers. We will return to this point in the Discussion.

Finally, consistent with the pattern found between skilled and less skilled child readers, less skilled child readers also showed a different pattern to adults (recall that the data pattern was very similar for skilled child and adult readers). We observed significant interactions with Type (Control-TL12), and Type (Control-TL13) in all dependent measures. This indicates that the differences between the control condition and the TL12 and TL13 conditions were greater for adults than less skilled child readers in all dependent measures, just as was seen in the comparison of skilled and less skilled child readers.

In summary, the cost of processing misspelled words was very similar for adults and skilled child readers: although lexical identification was fastest for correctly spelled words, internal letter transpositions were also relatively easy to process, in contrast to nonwords where the initial letter was manipulated. The cost of processing misspelled words was smaller, however, for less skilled children than either adults or skilled child readers. This suggests that they were using a different mechanism for word identification, possibly based on the activation of phonological cues to access lexical representations.

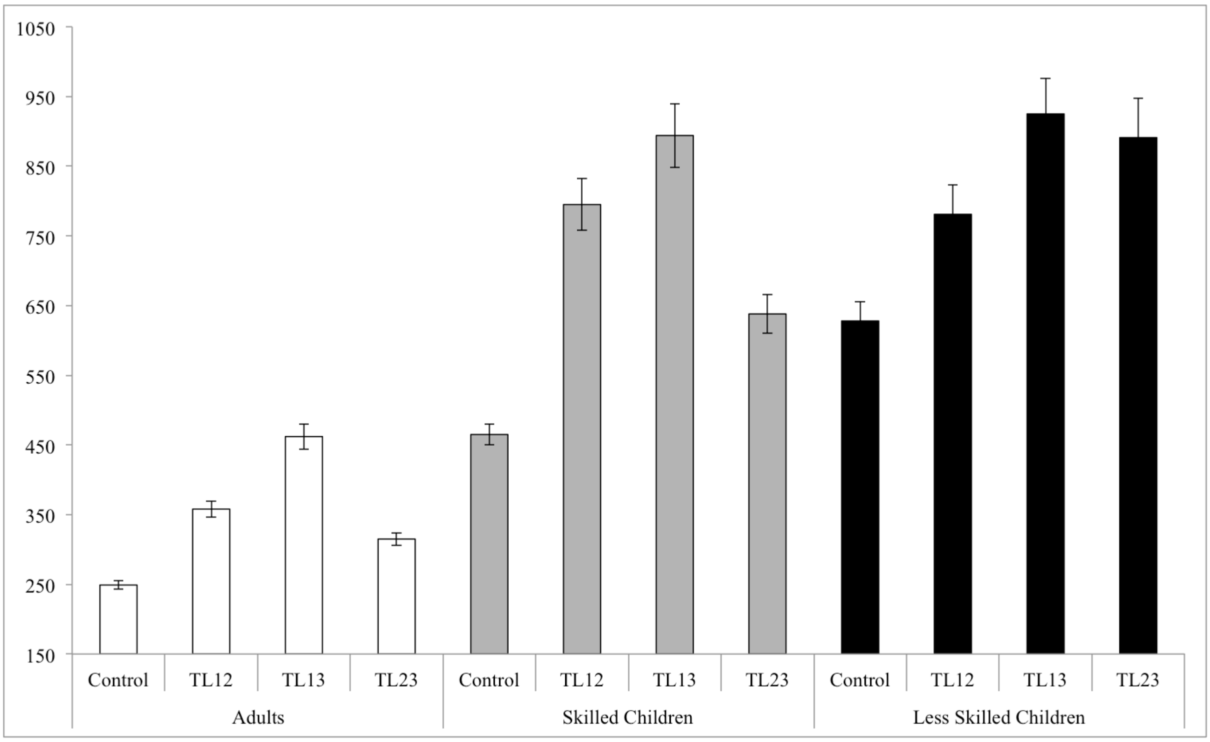
4.4.2.3. Effects of transposed letter position

Overall, the TL13 nonwords elicited longer fixation times than both TL12 and TL23 nonwords in single fixation and gaze duration. In addition, the TL23 nonwords received shorter fixation times than TL12 nonwords in gaze duration but not in earlier measures. This is consistent with previous evidence showing that internal letter transpositions cause less disruption to reading that initial letter transpositions (Pagán, Blythe & Liversedge, 2015; Perea & Lupker, 2003b, 2004, 2007; Rayner *et al.*, 2008; White *et al.*, 2008).

This pattern of effects was found to be highly similar in both adults and skilled child readers; none of the interactions between these groups and the letter position condition yielded significant effects in any dependent measure. Again, this indicates that adults and skilled child readers were encoding letter position information similarly, supporting previous evidence (Pagán, Blythe & Liversedge, 2015). Less skilled child readers, however, showed a different pattern of effects to both adults and skilled child readers.

Regarding the differences between skilled and less skilled child readers, two significant interactions were found in gaze duration only. First, the interaction with Type (TL13-TL23) showed that the difference between TL13 and TL23 nonwords was greater for skilled than for less skilled child readers. This indicates that skilled child readers are able to encode internal letter position information more flexibly than less skilled child readers (see Figure 4.1). Second, the interaction with Type (TL12-TL23) showed that the difference between TL12 and TL23 was greater for skilled than less skilled child readers. Here, the direction of the effect was different between the two groups. Skilled child readers again showed greater flexibility for internal than external manipulations (faster reading times on TL23 nonwords than on TL12 nonwords, consistent with the pattern of data seen for the adult readers). In contrast, less skilled child readers actually had slightly longer fixation times for TL23 than TL12 conditions. Looking at the stimuli (Appendix B), TL23 condition contained a non-existing, unpronounceable initial bigram, suggesting that children need some sort of phonological processing in order to activate the correct lexical representation from the misspelled words. The interaction between Group and Type (TL12-TL13) was not significant in any dependent measures, indicating that both groups of children had similar disruption to lexical processing when the first letter was manipulated.

Figure 4.1. Gaze duration data for the target word, showing effects of Group (adults vs. skilled vs. less skilled child readers) and Type (control vs. TL12 vs. TL13 vs. TL23). Error bars represent the *SE* for each condition.



Finally, we compared letter position effects between adults and less skilled child readers. In contrast to the pattern found between skilled and less skilled child readers, the results showed a reliable interaction with Type (TL12-TL13) in single and first fixation duration, indicating that the differences between TL12 and TL13 nonwords were greater for adults than less skilled child readers. This suggests that adults were able to encode flexible letter position information from adjacent pairs while less skilled child readers did not distinguish between adjacent or non-adjacent letters, the disruption was comparable when the first letter was manipulated. Note that this interaction was not significant between skilled and less skilled readers, indicating that letter position information for the first letter is more important for children than adult readers. In addition, the interaction with Type (TL13-TL23) was also reliable in all dependent measures, indicating that the differences in reading times between TL13 and TL23 nonwords were greater for adults than less skilled child readers. As in skilled child readers, adults were able to encode internal letter position information more flexibly than less skilled child readers. Finally, the interaction with Type (TL12-TL23), unlike skilled child readers, was not significant in any dependent measures.

4.4.2.4. Summary

Adults had shorter viewing times on the target word/nonword than both skilled and less skilled child readers. Further, skilled child readers had shorter viewing times on the target word/nonword than less skilled child readers. With respect to the experimental manipulations, the control condition (correctly spelled words) had the shortest viewing times for both adults and skilled child readers for all dependent variables, and for less skilled child readers in gaze duration. Regarding the effect of letter position, the pattern was very similar for adults and skilled child readers: words with transposed letters in position 13 caused the most disruption to reading, while words with transposed letters in position 23 caused the least disruption to reading. In contrast, the pattern of results in less skilled child readers differed from both adults and skilled child readers considerably. Although less skilled child readers exhibited a cost from processing misspelled words, the differences between misspelled words due to the position manipulation were diminished compared to adults and skilled child readers. This pattern indicates that both adults and skilled child readers were able to encode internal letter position information more flexibly than less skilled child readers. This differential pattern also supports the idea that less skilled child readers were using a mechanism based on the activation of partial phonological codes, that are in the fine-grained route from the Grainger and Ziegler's model, in order to identify words, while both adults and skilled child readers were using a mechanism based on activation of orthographic codes from the coarse-grained route for word identification.

4.5. Discussion

We conducted an experiment to investigate whether age and/or reading skill influenced letter position encoding during foveal processing in sentence reading. First, we discuss overall differences between the three groups of participants in terms of their eye movement behaviour during reading. Then, we discuss the cost of processing misspelled words as a function of participant's age and reading ability. Finally, we discuss how age and reading ability influence letter position encoding during sentence reading.

4.5.1. Overall developmental differences between the three groups of participants in reading

First, as predicted, we found that adults had shorter fixation durations, longer progressive saccade amplitudes, shorter reading times and made fewer fixations during sentence reading than both skilled and less skilled child readers. Furthermore, we found that adults had shorter reading times on the target words/nonwords than both skilled and less skilled child readers. This finding indicates that adults were able to retrieve and identify the correct lexical entry for the target words/nonwords faster than both skilled and less skilled child readers. These findings are consistent with previous studies investigating children's eye movement behaviour during reading that showed 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; Mancheva *et al.*, 2015; McConkie *et al.*, 1991; Rayner, 1986; Reichle *et al.*, 2013; Tiffin-Richards & Schroeder, 2015; Zang, Liang, Bai, Yan & Liversedge, 2012).

Second, also as predicted, we found that skilled and less skilled child readers differed from each other in mean fixation duration during sentence reading in both global and local analyses, indicating that reading ability also influenced the speed of lexical identification. Consistent with these increased fixation times, we also observed a trend in total sentence reading time such that less skilled child readers had longer total reading times than skilled child readers. Consistent with these eye movement data, although less skilled child readers did not have any reading difficulties that might indicate atypical development, they obtained significantly lower standardized scores on word reading, pseudoword decoding and comprehension than skilled child readers (see Table 4.1; indeed, we form the two groups of children on the basis of exactly these scores). Clearly the differences between adults and skilled child readers were much greater than between skilled and less skilled child readers. This is likely due to the fact that the difference in age between adults and children was more than 10 years, whilst the difference in skill between the two groups of children was based on differences in the standardized scores within at an age-appropriate level. These two types of group difference indicate that both age and skill influence processing time on words, supporting the Lexical Quality Hypothesis by Perfetti (2007, Perfetti & Hart, 2001, 2002). On the basis of this model, these group differences are attributable to the number of high-quality lexical representations that a reader has. Until now, previous research has demonstrated age-related decreases in reading times on words that were attributed to differences in the speed of lexical processing, but no theoretical explanation for this developmental change was specified. Our interpretation of these group differences on the basis of lexical quality is consistent with that of Luke *et al.* (2015), who found that adolescents aged 11-13 years old with high quality lexical representations had shorter gaze durations and made fewer refixations than adolescents with low quality lexical representations. Furthermore, this pattern of results extends previous evidence showing the influence of reading ability in eye movement behaviour with adults (Veldre & Andrews, 2014, 2015a, 2015b) to children.

Third, we expected that skilled child readers would have longer progressive saccade amplitudes than less skilled child readers but, unexpectedly, we did not find this effect. There are two possible explanations for this pattern. First, as described previously, the difference between the two groups of children was relatively small given that it was based on within age-appropriated reading (as opposed to the 10 year age gap between adults and children). Thus, it may be that any effect on saccade amplitude is simply smaller and more difficult to detect than an effect on fixation times. Alternatively, it could be attributed to the fact that both groups of children made a higher proportion of refixations than adults (adults refixated 54.5% of target words, whilst skilled children refixated 78.8% and less skilled children refixated 76.5% of target words). Given that within-word refixations typically have smaller amplitudes than between-word progressive saccades, then the increased proportion of refixations in children could be the reason why they made shorter saccades and more fixations than adults. The question that remains, however, is why skilled and less skilled child readers do not differ in refixation probability. Previous studies have shown that children make more refixations than adults, and the proportion of refixations decreases with age, and presumably also with reading ability (Blythe, 2014; Blythe *et al.*, 2009, 2011; Joseph *et al.*, 2009). Blythe *et al.* (2011) suggested that many of the refixations that children make are due to the fact that they need a second visual sample, especially on longer words. In this study, our target words/nonwords were 6-7 letters long; thus, it could be that the reason why both groups of children were making a similar number of refixations was that they needed a second visual sample. Note that this latter explanation is based on data from the target word analyses, whilst the overall pattern in saccade amplitude that we are trying to explain was based on the global analyses. Thus, we cannot make any strong claim about the underlying pattern of refixations as a key determinant of overall saccade amplitude; in fact, it may be the case that a number of factors (such as both the magnitude of group differences, and their refixation behaviour) may be influential here.

4.5.2. The cost of processing misspelled words

First, as predicted, we found that the cost of processing misspelled words was very similar for adults and skilled child readers. Both groups showed that lexical identification was fastest for correctly spelled words, and that internal letter transpositions were relatively easy to process compared to nonwords where the initial letter was manipulated. This is consistent with Pagán, Blythe and Liversedge (2015)'s study (see also Chapter 3 in this thesis), which showed that skilled child readers encoded letter position information flexibly, as adults do.

Second, it was predicted that the cost of processing misspelled words would be more pronounced in less skilled than skilled child readers. Unexpectedly, however, less skilled child readers showed reduced disruption to lexical processing from misspelled words than both adults and skilled child readers. This was mainly driven for the increased fixation times on the TL23 condition for less skilled child readers compared to skilled child and adult readers, showing that less skilled child readers had an overall difficulty to process misspelled words. It seems likely that this finding can be attributed to differences in the nature of lexical processing between the two groups of children. Our selected children were reading as expected for their age (as the WIAT-II assessment showed). We could assume, therefore, that they were in Phase 3 of Grainger and Ziegler's model. This model did not explicitly specify any developmental change once readers are in this phase. Again, there are two possible explanations for this pattern in the data. First, it may be that less skilled child readers were forced to employ an overt decoding strategy (as used in Phase 1 of the model) for processing transposed letter nonwords. We think, however, that this possibility is unlikely because there was no striking increase in processing times on the transposed letter nonwords relative to the correctly spelled words that would have indicated a shift from parallel to serial letter processing in the young and least skilled group of readers. Rather, the striking pattern here was the slightly surprising small magnitude cost to processing misspelled words. We believe, therefore, that all our readers were within Phase 3 of the model, and were using the coarse- and fine-grained routes for orthographic encoding of both the correctly spelled words and the transposed letter nonwords. Note that although both routes are considered orthographic routes in the phase 3 of the Grainger and Ziegler's model, the fine-grained route needs to access the phonological representations through a strict letter position encoding before activating the semantic representations; while the coarse-grained route needs to access directly the semantic representations through a flexible letter position encoding. On the basis of this assumption, we claim that our data suggest a relatively subtle shift in the nature of lexical processing between less skilled and skilled child readers, which cannot be accounted for the Grainger and Ziegler's model.

We propose that, in order to fully account for developmental changes in letter position encoding, it is necessary to combine information from both the Lexical Quality Hypothesis and Grainger and Ziegler's model. Specifically, we propose that within Phase 3 of Grainger and Ziegler's model, there may be a developmental change in the relative dominance of the two routes for orthographic encoding. Furthermore, we suggest that this shift might be attributable to the quality of the reader's lexical representations, strongly associated with their reading skill. In relatively less skilled readers who have recently established the two routes for orthographic encoding, we proposed that the fine-grained route is dominant due to the quality of their lexical representations. To reiterate, the Lexical Quality Hypothesis would suggest that the less skilled child readers should have a greater proportion of low quality lexical representations than either skilled child readers or adults; this premise was further supported by the overall group differences in fixation times in the present data set. These low quality representations are thought to have one or two of the following components - orthographic, phonological, and semantics information – underspecified or missing. On the basis that all children were typically developing, with no speech or language delays, and that all our stimuli were extensively pre-screened to ensure that they were suitable in difficulty for children of this age, then we assume that there should be no gross differences between the two groups of children in the representation of phonology and semantics. Given that these children were grouped based on their reading ability, then we think that the main underlying difference will be in the quality of their orthographic representations and so, accordingly, that is what we will focus on[10].

If orthographic information is missing from the lexical representation (e.g., if the child has not yet learned the printed form of the word), then they will only be able to use a serial recoding strategy to access semantics via phonological representations. This was clearly not the case in our present sample, as argued previously. Note that our stimuli were pre-screened, and children of similar age were able to read it. Thus, it must be that the orthographic information is relatively underspecified in the less skilled child readers, and

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[10] We are aware of the fact that future research should consider to use a direct measure of lexical quality such as a spelling test to stronger support this assumption.

this is what pushes them to use the fine-grained route in case that words are mispelled. Of course, this will vary on a word-by-word basis, depending on the particular input and their experience in processing that letter string. However, we should see overall group differences when averaged across a range of experimental stimuli. These less skilled readers would, therefore, need to encode letter position information in strict association with letter identity information in order to activate phonological and/or morphological cues for contiguous letters, using the fine-grained route. In this way, orthographic processing of a word's letters would occur in parallel, and thus, they would access semantic information directly from the visual input, but at the cost of having little flexibility in letter position encoding. Thus, with experience, and instruction, as reading skill increases, orthographic information becomes more precisely encoded in the reader's lexical representations and, as a consequence, the more dominant the coarse-grained route becomes predominantly used for lexical identification of misspelled words. In this route, letter position information is encoded flexibly, allowing rapid orthographic processing and word identification.

In sum, the present findings suggest that there is a developmental change in the relative dominance of one of the two orthographic codes that are proposed to exist in Grainger and Ziegler's model. Furthermore, the shift in dominance arises as a function of the quality of a reader's lexical representations, specifically when misspelled words were presented. Less skilled child readers with fewer, high quality lexical representations are likely to make predominant use of a mechanism based on the strict association of letter position and identity in order to access lexical representations via the fine-grained route. In contrast, both adults and skilled child readers with more, high quality lexical representations predominantly utilise a mechanism based on flexible letter position encoding that occurs via a coarse-grained route.

4.5.3. Effects of transposed letter position

As predicted, we observed that overall the TL13 condition had the longest viewing times for single fixation and gaze duration. This suggests that transpositions of non-adjacent letters resulted in increased time to retrieve the correct lexical candidate relative to transpositions involving adjacent letters (TL12 and TL23 conditions). This is consistent with previous evidence (e.g. Blythe, Johnson, Liversedge & Rayner, 2014; Chapter 3 of this thesis; Johnson, 2007; Johnson & Dunne, 2012; Johnson & Eisler, 2012; Johnson *et al.*, 2007; Perea & Lupker, 2003a, 2003b, 2004; Perea, Duñabeitia & Carreiras, 2008; White *et al.*, 2008; see also Briihl & Inhoff, 1995; Jordan *et al.*, 2003; Pagán, Blythe & Liversedge, 2015; Plummer & Rayner, 2012; Rayner *et al.*, 1980; Tiffin-Richards & Schroeder, 2015). In addition, TL12 condition had longer gaze durations than TL23 condition, suggesting that reading words with internal letters transposed is easier than when the first letter is transposed (as per Pagán, Blythe & Liversedge, 2015; Perea, & Lupker, 2003b, 2004; 2007), and supporting new models of letter position encoding such as the SOLAR (Davis, 1999, 2010); the Open Bigram (Grainger & van Heuven, 2003; Grainger *et al.*, 2006; Grainger & Ziegler, 2011), the Overlap (Gómez, Ratcliff & Perea, 2008) and the SERIOL (Whitney, 2001) models. These models assume a strict letter position encoding for initial letters and flexible letter position encoding for internal letters, due to initial letters playing an important role as lexical access units for word identification because the phonological code provided by the initial letters allows the reader to initiate lexical access..

Regarding developmental changes in letter position encoding as a function of the position of the letters manipulated, the pattern was very similar for adults and skilled child readers. We observed that words with transposed letters in position 13 caused the most disruption to reading; while words with transposed letters in position 23 caused less disruption to reading. First and foremost, this pattern of findings suggests that both adults and children perform letter position encoding similarly to identify words. This is also consistent with our previous study (Chapter 3 of this thesis; Pagán, Blythe & Liversedge, 2015), which showed that skilled child readers extracted letter position information from the parafovea regardless of letter identity information using a spatial coding mechanism (as per the SOLAR and SERIOL models) in a manner similar to adults. Consistently, we did not observe any differences between skilled child and adult readers in word reading stardardized scores (WIAT-II), suggesting that lexical processing was as efficient in skilled child readers as adults.

In contrast, less skilled child readers differed from both adults and skilled child readers considerably. First, for less skilled child readers the differences between TL13 and TL12 conditions were less pronounced compared to adults in early measures of processing (single and first fixation duration). In contrast, no significant differences were found between skilled and less skilled child readers in the early stages of processing. These results indicate that children, unlike adults, were unable to encode enough orthographic information during their first fixation of a transposed letter string for full lexical identification to occur (Blythe, 2014; Blythe *et al.*, 2011). This is also consistent with the previous finding that children made increased numbers of refixations compared to adults. Presumably, the increased refixation rates reflected the children's need to obtain a second visual sample of the letter string. Note that this effect held for both groups of children. Also, for less skilled child readers the differences between TL13 and TL23 conditions were less pronounced compared to both skilled child readers for gaze duration, and the adult readers for all target word/nonword reading time measures. This indicates that less skilled child readers were not able to encode internal letter positions as flexibly as skilled child readers and adults do. Finally, unexpectedly, the pattern of differences between TL12 and

TL23 was the same for adults and less skilled child readers in any dependent measures. Note that the interaction between Group (Adults vs Less skilled child readers) X Type (TL12 vs TL23) was not significant.

In contrast, skilled child readers spent more time fixating nonwords in the TL12 condition than TL23 condition, whereas less skilled child readers spent more time fixating nonwords in the TL23 condition than in the TL12 condition. Note that the pattern of these effects was similar between adults and skilled child readers. An explanation for this pattern of results is the following. In this study, both TL12 and TL23 conditions have limited useful phonological information (they were illegal or unpronounceable nonwords), compared to the TL13 condition (which were pronounceable nonwords). The fact that the disruption to lexical processing was less pronounced in less skilled child readers than both skilled child readers and adults might indicate that less skilled child readers did not realize that these were misspelled words, and they therefore used a mechanism based on the activation of phonological codes from the fine-coarse route in an attempt to lexically identify the correct word. In contrast, presumably, both skilled child readers and adults rapidly realized that TL12 and TL23 conditions were misspelled words, especially later during processing, after lexical identification occurred (gaze duration), and were able to activate the appropriate base word forms faster than was the case in the TL13 condition. This could likely be attributed to the fact that both skilled child and adult readers were encoding letter positions flexibly in relation to adjacent letters compared to non-adjacent letters. As mentioned earlier, we propose that a combination of the Lexical Quality Hypothesis and Grainger and Ziegler's model could offer an explanation for these findings. Taking these two theories together, it is possible that less skilled child readers exhibited dominant use of the fine-grained orthographic route for word identification due to fewer high quality lexical representations. In contrast, it seems likely that both skilled child and adult readers predominantly used the coarse-grained route for lexical identification due to the high quality of their lexical representations.

In summary, the present study provides novel findings about how letter position information is encoded during reading as a function of children's reading ability. We showed that the quality of readers' lexical representations influences the mechanism that they used to encode letter position information during sentence reading. More specifically, our findings reveal more fully that there is a developmental change that determines the relative dominance of the two orthographic routes proposed by Grainger and Ziegler's model. We argued that this developmental change is modulated by the quality of the lexical representations that readers have stored in their mental lexicon, that themselves influence how letter position information is encoded. Thus, skilled child and adult readers with more high quality lexical representations predominantly used the coarse-grained route underpinned by a flexible letter position encoding mechanism. In contrast, less skilled child readers with fewer high quality lexical representations predominantly used a fine-grained route in which a strict letter position encoding mechanism serves word identification.

CHAPTER 5: General Discussion

5.1. Summary of experimental findings

Previous research on letter position encoding during lexical processing has relied mainly on isolated word paradigms and on evidence from skilled adult readers. The aim of the present research was to systematically investigate developmental changes in letter position encoding during lexical processing, and to see how this affected eye movements during silent sentence reading. The influence of letter position encoding on eye movement behaviour has been investigated in two ways. First, by examining the time course of lexical and post-lexical processing in skilled adults. Second, by examining such processing in children, its relation with reading ability, and so, the lexical quality hypothesis, thereby establishing a possible explanation for the differences found in letter position encoding between adults and children. Indeed, the major contribution of the present work is in identifying a developmental change in letter position encoding as a function of a child reader's reading ability, reflected by the quality of their lexical representations.

The experiment reported in Chapter 2 (Pagán, Paterson, Blythe & Liversedge, 2015), investigated the influence of a target word's transposed neighbour earlier in the same sentence on the identification of that target word during reading. Until now, evidence using transposed letter neighbours has been inconsistent, and researchers have not agreed with whether transposed letter neighbours cause lexical competition (as substitution neighbours) or, in contrast, a failure of lexical access due to a target word's misidentification. This is important for two reasons: to understand how lexical selection occurs between similar candidates during lexical identification and, to consider transposed letter words as the same type of neighbours as substitution words are. Thus, in this experiment we examined whether the transposed letter neighbour that was encountered a few words earlier in the same sentence influenced the target word in skilled adults. The pattern of results in this experiment established that a word's transposed letter neighbour causes disruption to the processing of that word during reading. This experiment showed that this disruption was caused by a failure of word identification due to the misidentification of the word as its transposed letter neighbour, triggering post-lexical strategies of checking associated with revisits to the target word and regressions back to earlier portions of the text to confirm the identity of the word and its transposed letter neighbour. This pattern of findings using transposed letter words differed from the pattern of findings using substitution neighbours (Paterson *et al.*, 2009), in which they found evidence supporting lexical competition that occurred late during lexical processing (see also Perea & Pollatsek, 1998). We argued that the reason why transposed letter neighbours caused post-lexical checking rather than lexical competition was that transposed letter neighbours share more orthographic information (all the identities of their letters) than substitution neighbours (one letter different), and so they are perceptually more confusable, increasing the number of misidentifications. This experiment demonstrated that eye movement measures provide very detailed information about the time course of lexical and post-lexical processing during sentence reading, extending evidence from isolated word paradigms to eye movement measures during reading. In addition, it establishes how lexical selection occurs during sentence reading in readers with high level of proficiency in lexical processing, and good reading and writing experience. Further research will be necessary to determine whether the influence of encountering a word's transposed neighbour earlier in the sentence varies as function of the readers' age. As we further examined in experiments reported in Chapters 3 and 4, it would be also necessary to explore whether the pattern of effects or the time course or maybe both, could be modulated by reading ability, reflected by the quality of reader's lexical representations, rather than age. Note that to date, studies in children's reading do not differenciate between age and reading ability. Thus, Chapters 3 and 4 aimed to distinguish between these two variables.

In Chapter 3 (Pagán, Blythe & Liversedge, 2015), parafoveal pre-processing of letter identity and position information in a word's initial trigram by children and adults was explored. An invisible boundary paradigm was used to investigate developmental changes in parafoveal processing in English readers. Seven different previews were created as a function of the type of preview (identity versus transposed versus substituted) and the position of the letters manipulated (transposed or substituted letters in positions 1 and 2, 1 and 3, and 2 and 3). Results showed a transposed letter effect in position 13 for gaze duration in the pre-target words; and transposed letter effect in position 12 and 23 but not in position 13 in the target words for both adults and children, suggesting that there is a different time course of letter position encoding as a function of within-word location of the manipulated letters. Interestingly, the pattern of effects was found to be similar for adults and children, although children overall spent more time processing words compared to adults. This evidence supported the idea that, as adults do, children extracted letter position information independently from letter identity information from the parafovea, using a spatial coding mechanism (as per SOLAR (Davis, 1999, 2010) and SERIOL (Whitney, 2001) models). These results demonstrate that any differences between adults and children in this experiment in terms of global eye movement behaviour during reading must be attributed to developmental changes in aspects of reading that occur at a higher level than orthographic encoding. We suggested that the reason why we did not find any differences between adults and children in orthographic processing could be due to the fact that children in this experiment had a higher reading ability than expected for their age.

Thus, we suspected that it was reading skill, rather than chronological age per se, which determines a reader's ability to flexibly encode letter position information within words.

In order to further explore this interpretation more directly, the experiment reported in Chapter 4 (Pagán, Blythe & Liversedge, submitted) compared three groups of participants: adult, skilled and less skilled child readers as they read sentences with words that contained two transposed letters in three conditions (transposed letters in position 1 and 2, 1 and 3, and 2 and 3). Results showed that adults spent shorter time to process words than both skilled and less skilled child readers. Similarly, skilled children spent shorter times to process words than less skilled children. This finding suggested that both age and skill influence processing time on words. According to the Lexical Quality Hypothesis (Perfetti, 2007) these group differences could be attributed to the number of high-quality lexical representations that a reader has. In addition, results also showed the quality of readers' lexical representations influenced the mechanism that they used to encode letter position information during lexical processing in sentence reading. The pattern was very similar for adults and skilled child readers: words with transposed letters in position 13 caused the most disruption to reading, while words with transposed letters in position 23 caused the least disruption to reading. In contrast, the pattern of results in less skilled child readers differed from both adults and skilled child readers considerably. Although less skilled child readers showed a cost from processing misspelled words, the differences between misspelled words due to the position of the manipulation were diminished compared to both adults and skilled child readers. This pattern of findings suggested that both adults and skilled child readers were able to encode internal letter position information more flexibly than less skilled child readers. This differential pattern suggests that less skilled child readers with fewer, high quality lexical representations were likely to make predominant use of a mechanism based on the strict association of letter position and identity in order to access lexical representations, activating phonological codes from the fine-grained route in order to identify words. In contrast, both adults and skilled child readers with more, high quality lexical representations were likely to make predominantly use of a mechanism based on flexible letter position encoding, activating orthographic codes for word identification.

In summary, Chapter 2 showed that in skilled adult readers, a word's transposed letter neighbour presented earlier the same sentence caused target word misidentifications, disrupting post-lexical processing and initiating checking strategies to correctly identify both the transposed letter neighbour and the target word. Chapter 3 demonstrated that skilled child readers do pre-process orthographic information from the parafovea, similar to adults. Although skilled child readers made longer fixation times overall on words, the time course of letter position encoding as a function of the position of the letters manipulated was similar. Both adults and skilled child readers extracted letter position encoding from the parafovea using a spatial coding mechanism (as in SOLAR and SERIOL models). The experiment reported in Chapter 4 revealed that adults had shorter fixation times than both skilled and less skilled child readers. Similarly, skilled child readers had shorter fixation times than less skilled child readers. Both adults and skilled child readers showed the same pattern of effects: words with transposed letters in position 13 caused the most disruption to reading, while words with transposed letters in position 23 caused the least disruption to reading. In contrast, although less skilled child readers showed a cost from processing misspelled words, the differences between misspelled words due to the position of manipulation were diminished compared to both adults and skilled child readers.

5.2. Implications for models of letter position encoding

The present research provides further evidence about both the time course of lexical access and lexical selection during lexical processing, extending previous evidence using isolated word recognition paradigms to silent sentence reading. Models of isolated word recognition were designed to explain lexical identification only in the case of isolated words presented in the fovea (e.g., data from lexical decision-type tasks), and they are not intended to explain how lexical identification occurs in sentence reading; nor whether letter identity and position encoding imply similar visual processes in foveal and parafoveal vision. Thus, the present work underlines the necessity for an account of how lexical processing occurs during reading, an account that can be realistically incorporated into models of eye movement control.

5.2.1. Lexical selection

Chapter 2 showed that transposed letter neighbours do not cause disruption to processing in the same way as substitution neighbours. Although both types of neighbours cause longer fixation times during processing of the target word, transposed letter neighbours cause disruption to post-lexical processing, while substitution neighbours cause lexical competition at later stages of lexical identification (see Paterson *et al.*, 2009). We proposed that this differential pattern between transposed and substituted neighbours can be explained by the fact that transposed letter neighbours are perceptually more confusable than substitution neighbours, being more likely to cause misidentification of the correct candidate rather than lexical competition. Although there are some models (e.g., Gómez *et al.*, 2008; Norris *et al.*, 2010) that assume a noisy operation of the position-encoding mechanism and that could account for a word's misidentification, these models could not explain the effects found in post-lexical processing because they were designed to explain the processes involved in isolated-word identification, not post-lexical processing.

5.2.2. Lexical processing

The present research further supports the claim that letter position information is encoded flexibly during lexical processing (Chapters 3 and 4). Furthermore, clear evidence has been shown for the differential pattern of letter position encoding found for initial and internal letters. Specifically, initial letter identity and position information is encoded more strictly due to its special role as a lexical access unit to facilitate word identification, while letter identity and position information is encoded flexibly. This differential pattern is consistent with new isolated word recognition models such as the Open Bigram (Grainger *et al.*, 2006; Grainger & Ziegler, 2011), SOLAR (Davis, 1999, 2010), SERIOL (Whitney, 2001) and Overlap (Gómez *et al.*, 2008) models.

More importantly, the present research reveals that letter position information is encoded through a spatial coding mechanism such as in SOLAR and SERIOL models. This was supported by a similar pattern of findings observed in the simulation of the Spatial Coding Model (SOLAR) to that observed in the eye movement experiment in Chapter 3. Although further research needs to be carried out to determine whether individual letters or bigrams are the units over which orthographic information is encoded during lexical processing in both fovea and parafoveal processing, the present findings are consistent with evidence from isolated word recognition paradigms.

Finally, one of the limitations of the flexible letter position encoding models is that they cannot account for developmental changes on letter position encoding (except for the Grainger & Ziegler's model, see below). These models assume that the transposed letter effect reflects the noisy operation of the position-coding mechanism and, thus, is not influenced by reading development (see Gómez *et al.*, 2008; Norris, Kinoshita & van Casteren, 2010). Thus, these models need to develop accounts that incorporate some mechanism in order to explain the developmental changes on letter position encoding.

5.2.3. The Grainger and Ziegler's model (2011)

Only Grainger and Ziegler's model can account for developmental changes in letter position encoding during isolated word identification, although even this model is quite limited in this regard. The model explicitly incorporates developmental change during lexical processing, via three phases: (1) very early reading (overt, serial decoding); (2) early parallel processing of the letters within a word; leading to (3) the use of both a fine-grained (strict letter position encoding) and a coarse-grained route (flexible letter position encoding) for parallel orthographic encoding. There is no further developmental change in these two routes for orthographic encoding. The present research suggests that there is a developmental change in the relative dominance of one of the two orthographic codes that are proposed to exist in Grainger and Ziegler's model.

The experiment in Chapter 4 showed that while both adults and skilled child reader showed a similar pattern of effects (as in Chapter 3), the pattern of effects found for less skilled child readers differed considerably from both adults and skilled child readers. This clearly supports the proposal that there is a developmental change in the relative dominance of these two orthographic codes, as a function of the quality of reader's lexical representations. Specifically, it was found that both adults and skilled child reader encoded letter position information flexibly via the coarse-grained route, while less skilled child readers encoded letter position information in association with letter identity information via the fine-grained route. Further research is needed to develop an account that can fully explain developmental changes in letter position encoding during sentence reading as a function of the quality of reader's lexical representations.

5.3. Developmental changes in lexical processing

5.3.1. Parafoveal processing

Until very recently, relatively little was known about children's parafoveal pre-processing during reading, and how this skill develops with age and reading ability. Some studies showed that the perceptual span is reduced in children compared to adults (Häikiö *et al.*, 2009; Sperlich *et al.*, 2015; Rayner, 1986). In the experiment in Chapter 3, however, children were able to extract letter position information before the target was directly fixated, demonstrating that skilled child readers were able to pre-process orthographic information from the parafoveal words, as we know that adults do. This experiment demonstrates that orthographic processing in skilled children aged 8-9 years old is both as efficient and starts as early as in adults, easing lexical identification. The fact that children's reading would benefit from parafoveal processing also suggests that their foveal processing is also more efficient than younger or less skilled children. In this experiment, our children had a reading age higher than expected for their age, thus it could be possible that their lexical processing was very good, allowing them to benefit from parafoveal processing. As I will discuss in the next section, the fact that adults and skilled children aged 8-9 years old do pre-process orthographic information similarly from the parafovea, it does not mean that there are not differences in their reading. These differences, however, seem not to be associated with processing that occurs during orthographic encoding but at later stages such us syntactic or semantic processing levels. Further research, thus, is needed to examine developmental changes in parafoveal processing and the type of information that can be extracted from the parafovea.

5.3.2. Foveal processing

Until now, most eye movement studies conducted with children have used age as a variable to show differences in eye movement behaviour, however, the present research goes a step further and explores the influence of reading ability within the same group age. The present research establishes a possible explanation for the differences found in lexical processing between adults and children, and more specifically, in letter position encoding as a function of children's reading ability.

In Chapter 3, we found that adults had shorter reading times than children. This is a quite robust finding in the eye movement literature in children. Until now, these differences have been explained by suggesting that lexical processing is slow in children compared adults, but no theoretical explanation of the nature and manner of change has been articulated (Mancheva *et al.*, 2015; Reichle et *al.*, 2013). According to Perfetti's Lexical Quality Hypothesis (Perfetti, 2007), these age-related differences could be explained by differences in the quality of lexical representations. In this theory, there is a continuum on which lexical representations vary in quality as a function of the reader's knowledge about words, vocabulary and their reading and writing experience. Thus, adults with more years of reading experience will have more high quality lexical representations, and as a consequence, more efficiency in lexical processing whereas children with less years of reading experience will have fewer high quality lexical representations, and as a consequence, they will need more time for lexical identification. This theoretical framework has been validated with the findings in Chapter 4, which replicated the overall longer reading times for skilled child readers compared to adults; and more interestingly, directly supported the theory by showing differences in reading times as a function of children's reading ability.

Finally, as mentioned before, the mechanism to encode letter position information during word identification varies as a function of the quality of the reader's lexical representations. The differences between the two groups of children in Chapter 4 were in the quality of their orthographic representations because they were grouped based on their reading ability. We suggested that less skilled child used the fine-grained route in the Grainger and Ziegler's model because the orthographic information of the lexical representation was underspecified. Thus, they need to encode letter position information in strict association with letter identity in order to activate phonological codes for word identification. In contrast, adults and skilled child readers with more precise orthographic information in their lexical representations use the coarse-grained route in the Grainger and Ziegler's model, encoding letter position information flexibly.

Although the Lexical Quality Hypothesis does not account for letter position encoding during lexical identification because it is a general theory of reading skill, the present research further demonstrates that the quality of a reader's lexical representations influence the mechanism of letter position encoding during sentence reading. Thus, further research is needed to develop an account of this theory that can explain how the quality of lexical representations influences letter position encoding during word identification in sentence reading.

5.4. Implications for model's of eye movement control

This research underlines the necessity for an account of how lexical processing occurs in relation to fixations and saccades during normal reading, that is, an account that can be incorporated into models of eye movement control. In this work, models of isolated word recognition have been used to generate predictions about how word identification might proceed (at least to some degree) during normal reading. Although some computational models of eye-movements during reading distinguish between lexical and post-lexical processing (e.g., the E-Z Reader Model, see Reichle, 2011), the nature of lexical processing in such models remains underspecified, reflecting the current position in understanding of the processes underlying reading. The present research is an attempt to move towards a fuller understanding of the processes involved in lexical processing that can be realistically incorporated into models of eye-movement control. For this, further research should aim to explain how lexical processing is distributed across successive fixations and employs both partial (parafoveal), as well as fully available (foveal) visual information for word recognition (see Rayner & Liversedge, 2011; Grainger, 2000, for similar views).

In contrast to the SWIFT model that has not yet been extended to account for children's eye movements, the E-Z Reader model has attempted to account for changes associated with reading development (Mancheva *et al.*, 2015; Reichle *et al.*, 2013). Reichle *et al.,* (2013) tested two hypotheses that could explain developmental changes in eye movement: linguistic proficiency and oculomotor tuning. Simulations showed that reducing only the parameter associated with lexical processing (α_1) was enough to observe the basic pattern of eye movement behaviour in children, consistent with the suggestion that improvements in reading with development reflect increased efficiency in lexical processing. Mancheva *et al.,*) extended previous research, using simulations with child data. They found that one of the major sources of variance was children's orthographic knowledge, suggesting that orthographic precision has an important contribution to skilled lexical processing. Further research is required to extend this evidence to theoretical accounts that can accommodate developmental changes of letter position encoding as a function of the quality of reader's lexical representation during lexical processing in sentence reading.

5.5. Conclusion

The experiments presented in this thesis have extended our understanding of how letter position information is encoded during sentence reading by combining evidence and considering theoretical framework from three different fields: eye movement control, children's literacy and isolated word recognition. The findings in Chapter 2 contribute to establish the time course of the processes that occur during lexical and post-lexical processing during sentence reading by skilled readers, extending evidence from isolated word paradigms to eye movement measures during reading. Chapters 3 and 4 demonstrate a developmental change in letter position encoding as a function of the quality of the reader's lexical representations. The present research combines information from both the Lexical Quality Hypothesis and Grainger and Ziegler's model (2011) in order to fully account for developmental changes in letter position encoding during sentence reading.

APPENDIX A: LMM Analysis Summary Tables

Table 3.1. LMM Model 1 for single, first fixation and gaze duration in the pre-target word in Chapter 3.

	Single Fixation Duration				First Fixation Duration				Gaze Duration			
	b	*SE*	*t*	CI	b	*SE*	*T*	CI	b	*SE*	*t*	CI
Adults, Identity (Int)	5.28	0.03	165.0	5.22-5.34	5.27	0.03	187.4	5.21-5.32	5.32	0.03	156.7	5.26-5.39
Adults, Children	0.27	0.05	5.7	0.18-0.36	0.22	0.04	5.8	0.15-0.29	0.36	0.04	8.1	0.28-0.45
Adult, TL12	0.03	0.03	1.2	-0.02-0.10	0.03	0.03	1.1	-0.02-0.08	0.02	0.03	0.7	-0.04-0.09
Adult, TL13	0.02	0.03	0.7	-0.04-0.08	0.01	0.03	0.3	-0.04-0.06	-0.01	0.03	-0.3	-0.07-0.06
Adult, TL23	0.02	0.03	0.7	-0.04-0.08	0.02	0.03	0.8	-0.03-0.08	0.02	0.03	0.7	-0.04-0.09
Adult, SL12	0.03	0.03	0.8	-0.03-0.09	0.02	0.03	0.8	-0.03-0.08	0.02	0.03	0.6	-0.05-0.08
Adults, SL13	0.04	0.03	1.2	-0.02-0.10	0.01	0.03	0.4	-0.04-0.07	0.04	0.03	1.1	-0.03-0.10
Adult,SL23	0.05	0.03	1.5	-0.01-0.11	0.03	0.03	1.0	-0.03-0.08	0.03	0.03	0.9	-0.03-0.10
Children*TL12	0.00	0.05	0.0	-0.10-0.10	-0.05	0.04	-1.4	-0.13-0.02	-0.05	0.05	-1.0	-0.14-0.04
Children*TL13	-0.07	0.05	-1.3	-0.17-0.03	-0.03	0.04	-0.9	-0.11-0.04	-0.07	0.05	-1.5	-0.16-0.02
Children*TL23	0.01	0.05	0.9	-0.09-0.11	-0.00	0.04	-0.1	-0.08-0.07	-0.01	0.05	-0.3	-0.10-0.08
Children*SL12	-0.10	0.05	-1.8	-0.20-0.00	-0.00	0.04	-0.9	-0.11-0.04	-0.03	0.05	-1.1	-0.14-0.04
Children*SL13	-0.10	0.05	-1.9	-0.20-0.00	0.00	0.04	0.1	-0.07-0.08	-0.03	0.05	-0.7	-0.12-0.06
Children*SL23	-0.02	0.05	-0.4	-0.13-0.08	-0.03	0.04	-0.7	-0.10-0.05	-0.05	0.05	-1.1	-0.14-0.04

Note: b = regression coefficient; *SE* = standard error; *t* = test statistic (b/SE); CI = Confidence Intervals (2.5%-97.5%).

Table 3.3. LMM Model 2 and additional contrasts for single, first fixation and gaze duration in the pre-target word in Chapter 3

	Single Fixation Duration				First Fixation Duration				Gaze Duration			
	b	*SE*	*t*	CI	b	*SE*	*t*	CI	b	*SE*	*t*	CI
Intercept	5.42	0.02	271.6	5.38-5.46	5.39	0.02	323.7	5.35-5.42	5.51	0.02	268.8	5.46-5.55
Group	0.22	0.03	6.7	0.16-0.28	0.19	0.03	6.9	0.14-0.25	0.32	0.03	9.8	0.26-0.38
Type	-0.02	0.01	-1.1	-0.05-0.01	0.00	0.01	0.5	-0.02-0.03	0.15	0.01	1.1	-0.01-0.04
Position (12-13)	-0.02	0.02	-1.0	-0.05-0.02	-0.00	0.01	-0.2	-0.03-0.02	-0.01	0.02	-0.0	-0.04-0.02
Position (13-23)	0.04	0.02	2.3	0.01-0.08	0.01	0.01	1.1	-0.01-0.04	0.02	0.02	1.3	-0.01-0.05
Group X Type	-0.06	0.03	-1.9	-0.11-0.00	0.01	0.02	0.6	-0.03-0.05	-0.00	0.03	-0.0	-0.05-0.05
Group X Pos (12-13)	-0.03	0.04	-0.9	-0.10-0.04	0.03	0.03	1.0	-0.03-0.08	-0.00	0.03	-0.1	-0.07-0.06
Group X Pos (13-23)	0.07	0.04	2.0	0.00-0.14	0.00	0.03	0.0	-0.05-0.05	0.02	0.03	0.6	-0.04-0.08
Type X Pos (12-13)	0.06	0.04	1.8	-0.01-0.13	0.02	0.03	0.8	-0.03-0.07	0.07	0.03	2.1	0.00-0.13
Type X Pos (13-12)	0.01	0.04	0.3	-0.06-0.08	-0.03	0.03	-1.1	-0.08-0.02	-0.07	0.03	-2.3	-0.14-(-0.01)
GroupXTypeXPos (12-13)	0.07	0.07	0.9	-0.07-0.21	0.02	0.05	0.4	-0.09-0.12	0.04	0.06	0.6	-0.09-0.17
GroupXTypeXPos(13-23)	0.00	0.07	0.0	-0.14-0.14	-0.06	0.05	-1.1	-0.17-0.04	-0.07	0.07	-1.0	-0.20-0.06
Position (12-23)	-0.02	0.02	-1.4	-0.06-0.01	-0.01	0.02	0.6	-0.04-0.01	-0.01	0.02	-0.9	-0.05-0.02
Group X Pos (12-23)	-0.04	0.04	-1.2	-0.11-0.03	-0.03	0.03	-1.0	-0.08-0.25	-0.02	0.03	-0.5	-0.08-0.05
Type X Pos (12-23)	-0.07	0.04	-2.0	-0.14-0.00	0.01	0.03	0.3	-0.04-0.06	0.01	0.03	0.2	-0.06-0.07
GroupXTypeXPos(12-23)	-0.06	0.07	-0.8	-0.20-0.08	0.04	0.05	0.0	-0.06-0.15	0.03	0.06	0.4	-0.10-0.16

Note: b = regression coefficient; *SE* = standard error; *t* = test statistic (b/SE); CI = Confidence Intervals (2.5%-97.5%).

Appendix A

Table 3.4. LMM Model 1for single, first fixation and gaze duration in the target word in Chapter 3.

	Single Fixation Duration				First Fixation Duration				Gaze Duration			
	b	*SE*	*t*	CI	b	*SE*	*t*	CI	b	*SE*	*t*	CI
Adults, Identity (Int)	5.40	0.04	148.4	5.33-5.47	5.36	0.03	159.6	5.30-5.43	5.47	0.04	120.3	5.38-5.55
Adults, Children	0.31	0.05	5.8	0.21-0.42	0.22	0.04	5.0	0.14-0.31	0.50	0.06	8.6	0.38-0.61
Adult, TL12	0.05	0.03	1.4	-0.02-0.11	0.04	0.03	1.1	-0.03-0.10	0.07	0.04	1.9	-0.00-0.14
Adult, TL13	0.12	0.03	3.6	0.06-0.19	0.11	0.03	3.3	0.04-0.18	0.13	0.04	3.6	0.06-0.20
Adult, TL23	0.02	0.03	0.7	-0.04-0.09	0.03	0.03	1.0	-0.03-0.10	0.03	0.04	0.8	-0.04-0.10
Adult, SL12	0.14	0.03	4.0	0.07-0.20	0.09	0.03	2.8	0.03-0.16	0.14	0.04	4.1	0.07-0.21
Adults, SL13	0.16	0.03	4.5	0.09-0.23	0.13	0.03	3.7	0.06-0.19	0.16	0.04	4.4	0.09-0.23
Adult, SL23	0.11	0.03	3.3	0.05-0.18	0.10	0.03	3.0	0.03-0.17	0.15	0.04	4.0	0.07-0.22
Children*TL12	0.05	0.06	0.8	-0.07-0.16	0.02	0.05	0.4	-0.07-0.11	-0.02	0.05	-0.3	-0.11-0.08
Children*TL13	0.06	0.06	1.0	-0.06-0.18	-0.00	0.05	-0.1	-0.09-0.08	0.04	0.05	0.8	-0.06-0.14
Children*TL23	0.06	0.06	1.0	-0.05-0.17	0.03	0.05	0.7	-0.06-0.12	-0.00	0.05	-0.0	-0.10-0.09
Children*SL12	0.14	0.06	2.2	0.01-0.26	0.01	0.05	0.3	-0.07-0.10	-0.02	0.05	-0.4	-0.11-0.08
Children*SL13	0.01	0.06	0.1	-0.11-0.13	-0.05	0.05	-1.1	-0.14-0.04	-0.05	0.05	-1.0	-0.15-0.04
Children*SL23	0.12	0.06	2.0	0.00-0.23	0.00	0.05	0.1	-0.09-0.10	-0.03	0.05	-0.5	-0.12-0.07

Note: b = regression coefficient; *SE* = standard error; *t* = test statistic (b/SE); CI. = Confidence Intervals (2.5%-97.5%).

Table 3.6. LMM Model 2 and additional contrasts for single, first fixation and gaze duration in the target word in Chapter 3.

	Single Fixation Duration				First Fixation Duration				Gaze Duration			
	b	*SE*	*t*	CI	b	*SE*	*t*	CI	b	*SE*	*t*	CI
Intercept	5.69	0.02	242.2	5.65-5.74	5.56	0.02	292.7	5.52-5.60	5.82	0.03	195.5	5.76-5.88
Group	0.39	0.04	9.7	0.31-0.47	0.23	0.03	6.6	0.16-0.30	0.48	0.05	10.1	0.39-0.58
Type	0.09	0.02	4.9	0.05-0.13	0.03	0.01	2.5	0.01-0.06	0.06	0.01	4.0	0.03-0.08
Position (12-13)	0.02	0.02	0.7	-0.03-0.06	0.03	0.02	1.8	-0.00-0.06	0.04	0.02	2.5	0.01-0.08
Position (13-23)	-0.04	0.02	-2.0	-0.09-0.00	-0.03	0.02	-1.6	-0.06-0.01	-0.06	0.02	-3.4	-0.09-(0.02)
Group X Type	0.04	0.04	1.0	-0.3-0.11	-0.03	0.03	-1.0	-0.08-0.02	-0.04	0.03	-1.4	-0.09-0.01
Group X Pos (12-13)	-0.05	0.05	-1.1	-0.14-0.04	-0.05	0.03	-1.4	-0.11-0.02	0.01	0.03	0.4	-0.05-0.08
Group X Pos (13-23)	0.05	0.04	1.2	-0.03-0.13	0.05	0.03	1.5	-0.02-0.11	-0.01	0.03	-2.4	-0.08-0.06
Type X Pos (12-13)	-0.13	0.05	-2.9	-0.22-(-0.04)	-0.06	0.03	-1.9	-0.13-0.00	-0.09	0.03	-2.8	-0.16-(-0.03)
Type X Pos (13-12)	0.11	0.04	2.7	0.03-0.20	0.06	0.03	1.9	-0.00-0.13	0.12	0.03	3.5	0.05-0.19
GroupXTypeXPos (12-13)	-0.15	0.09	-1.6	-0.34-0.03	-0.04	0.06	-0.7	-0.17-0.08	-0.09	0.07	-1.4	-0.23-0.04
GroupXTypeXPos(13-23)	0.12	0.09	1.4	-0.05-0.29	0.02	0.07	0.3	-0.11-0.15	0.06	0.07	0.9	-0.07-0.20
Position (12-23)	0.03	0.02	1.2	-0.02-0.07	-0.00	0.02	-0.2	-0.03-0.03	0.02	0.02	1.0	-0.02-0.05
Group X Pos (12-23)	0.00	0.04	0.1	-0.08-0.09	-0.00	0.03	-0.0	-0.07-0.06	-0.00	0.03	-0.1	-0.07-0.06
Type X Pos (12-23)	0.00	0.04	0.1	-0.08-0.09	-0.00	0.03	-0.0	-0.07-0.06	-0.03	0.03	-0.8	-0.09-0.04
GroupXTypeXPos(12-23)	-0.00	0.09	0.0	-0.17-0.17	0.02	0.07	0.4	-0.10-0.15	0.02	0.07	0.4	-0.11-0.16

Appendix A

Table 4.3. LMM Model for single, first fixation and gaze duration in the target word in Chapter 4.

	Single Fixation Duration				First Fixation Duration				Gaze Duration			
	b	*SE*	*t*	CI	b	*SE*	*t*	CI	b	*SE*	*t*	CI
Intercept	5.86	0.03	210.9	5.80-5.91	5.63	0.02	276.0	5.60-5.67	6.12	0.04	167.3	6.05-6.20
Group1 (Ads-Ch_SK)	0.38	0.06	6.9	0.27-0.49	0.25	0.05	5.6	0.23-0.35	0.58	0.07	8.3	0.44-0.71
Group2 (Ch_SK-Ch_L_SK)	0.14	0.06	2.2	0.02-0.27	0.07	0.05	1.5	-0.02-0.17	0.15	0.03	2.0	0.01-0.29
Type1 (Control-TL12)	0.16	0.04	4.3	0.09-0.23	0.07	0.02	3.3	0.03-0.11	0.27	0.03	9.6	0.22-0.33
Type2 (TL12- TL13)	0.08	0.04	2.1	0.00-0.17	0.03	0.02	1.2	-0.02-0.07	0.13	0.03	4.6	0.07-0.19
Type3 (TL13-TL23)	-0.13	0.04	-3.0	-0.21-(-0.04)	-0.03	0.02	-1.3	-0.07-0.01	-0.18	0.07	6.4	-0.24-(-0.13)
Group1 X Type1	-0.00	0.08	-0.1	-0.17-0.16	-0.08	0.05	-1.5	-0.18-0.02	0.08	0.07	1.2	-0.05-0.21
Group2 X Type1	-0.18	0.10	-1.8	-0.38-0.02	-0.09	0.05	-1.7	-0.20-0.01	-0.24	0.07	-3.3	-0.38-(-0.10)
Group1 X Type2	-0.08	0.10	-0.8	-0.27-0.11	-0.06	0.05	-1.2	-0.16-0.04	-0.12	0.07	-1.8	-0.25-0.01
Group2 X Type2	-0.12	0.11	-1.9	-0.34-0.10	-0.04	0.05	-0.8	-0.15-0.06	0.04	0.07	0.6	-0.10-0.19
Group1 X Type3	0.05	0.09	0.6	-0.13-0.24	0.10	0.05	1.9	-0.02-0.20	0.05	0.07	0.7	-0.09-0.18
Group2 X Type3	0.21	0.12	1.8	-0.02-0.44	0.06	0.05	1.2	-0.04-0.17	0.22	0.07	3.1	0.08-0.37
Type4 (Control-TL13)	-0.23	0.05	-4.4	-0.33-(-0.13)	-0.08	0.03	-2.9	-0.13-(-0.02)	-0.36	0.03	-10.3	-0.43-(-0.29)
Type5 (Control-TL23)	-0.03	0.05	-0.5	-0.14-0.08	-0.04	0.03	-1.4	-0.11-0.02	-0.10	0.04	-2.3	-0.17-(-0.01)
Type6 (TL12-TL23)	0.06	0.05	1.2	-0.04-0.15	0.02	0.03	0.9	-0.03-0.08	0.10	0.03	2.7	0.03-0.16

Table 4.3 cont.

	Single Fixation Duration				First Fixation Duration				Gaze Duration			
	b	*SE*	*t*	CI	b	*SE*	*t*	CI	b	*SE*	*t*	CI
Group1 X Type4	0.10	0.12	0.9	-0.13-0.35	0.15	0.06	2.4	0.03-0.27	0.11	0.08	1.3	-0.05-0.26
Group2 X Type4	0.32	0.14	2.3	0-.5-0.59	0.12	0.07	1.8	0.03-0.27	0.18	0.09	2.1	0.01-0.36
Group1 X Type5	-0.05	0.13	0.4	-0.29-0.19	-0.02	0.07	-0.3	-0.16-0.12	-0.13	0.09	1.4	-0.31-0.05
Group2 X Type5	-0.03	0.15	-0.2	-0.32-0.27	0.03	0.08	0.4	-0.12-0.18	0.02	0.10	0.2	-0.18-0.22
Group1 X Type6	0.05	0.11	0.4	-0.17-0.28	-0.02	0.06	-0.4	-0.14-0.10	0.14	0.08	1.7	-0.02-0.30
Group2 X Type6	-0.08	0.14	-0.6	-0.34-0.19	-0.03	0.07	-0.5	-0.16-0.10	-0.27	0.09	-3.1	-0.44-(-0.11)
Group3 (Ads-Ch_L_SK)	-0.54	0.06	-9.2	-0.66-(-0.43)	-0.34	0.05	-6.7	-0.44-(-0.24)	-0.75	0.08	-9.5	-0.90-(-0.59)
Group3 X Type1	0.17	0.08	2.1	0.01-0.32	0.17	0.05	3.1	0.06-0.27	0.14	0.07	2.0	0.00-0.28
Group3 X Type2	0.21	0.09	2.3	0.03-0.38	0.11	0.05	2.0	0.00-0.21	0.09	0.07	1.2	-0.05-0.22
Group3 X Type3	-0.27	0.10	-2.7	-0.45-(-0.08)	-0.16	0.05	-3.0	-0.27-(-0.06)	-0.26	0.07	-3.7	-0.40-(-0.12)
Group3 X Type4	-0.42	0.12	-3.6	-0.65-(-0.19)	-0.28	0.06	-4.2	-0.40-(-0.15)	-0.29	0.09	-3.3	-0.46-(-0.12)
Group3 X Type5	0.10	0.12	0.8	-0.14-0.34	-0.01	0.08	-0.1	-0.15-0.14	0.12	0.10	1.2	-0.07-0.32
Group3 X Type6	0.01	0.11	0.1	-0.20-0.21	0.06	0.06	0.9	-0.07-0.19	0.11	0.09	1.3	-0.06-0.28

Note: b = regression coefficient; *SE* = standard error; *t* = test statistic (b/SE); CI = Confidence Intervals (2.5%-97.5%)

APPENDIX B: Stimulus Materials

Sentences used in Chapter 2 Experiment (TL/Control prime and target words in bold):

The sculpture's face had a great **smile/shine** despite the nasty **slime** that the damp had caused

The odd painting had **angels/ankles** without feet and strange **angles** in the corners.

There was a metal pin on the old **bolt/belt** as well as a dark **blot** next to the hole.

In the film, the car **braked/bucked** before parking while the dog **barked** furiously.

Maggie ignored the sounds from the **carol/canal** as the lovely **coral** on tv caught her attention.

We were distracted and a man stole our **coats/coach** on the way to the south **coast** of England.

Anna gave her daughter the **diary/dolly** when she returned from the **dairy** on her school trip.

On the day he was **fired/freed**, he ordered **fried** eggs and bacon for breakfast.

The man selected the **form/farm** very carefully **from** amongst several possible alternatives.

The man found the **scared/snared** animal and wrapped his **sacred** football shirt around it.

Every morning, the engineer unloads some building **signs/sands** while his mate **sings** a silly song.

I checked that my assistant had **slept/swept** well and had also **spelt** the advert correctly.

Every day the maid cleaned her master's **silver/shaver** then got a **sliver** of bread for her breakfast.

My new desk calendar has coloured **spots/slots** where each week **stops** and a new one begins.

The experimental artist will **wrap/whip** it and **warp** it to try and get the shape she wants.

At the lake, Charlie removed the **slime/spine** from the fish with a great **smile** on his face.

As the teacher talked to the kids about different **angles/tigers**, the bored girl drew **angels** in her book.

The child drew a huge **blot/boot** in his textbook and shouted to **bolt** the door at the same time.

The boss **barked/backed** away at James when he **braked** the car abruptly in the car park.

The girl looked at a picture of a rare **coral/camel** while listening to a famous **carol** on the radio.

My parents saw nice drawings of the Italian **coast/coins** when collecting their **coats** from the hotel.

The farmer cleaned the **dairy/dirty** spillage before writing a note in his **diary** about the incident.

The dish was ruined when the chef **fried/faked** it and he was **fired** the next week.

As the director saw him coming **from/film** the cinema/in the cinema, an actor expected the new contract **form** to arrive.

The woman checked her **sacred/stored** collection as she was **scared** that the removal men might damage it.

When upset, my daughter usually **sings/sinks** in the bath with two **signs** on the door that say “No Entry”.

The lady ensured that her cheque had been correctly **spelt/spent** and then **slept** deeply through the night.

At the party, I took the thin **sliver/server** away from the **silver** plates and into the kitchen.

When the artist **stops/shows** his work the blank **spots** on the canvas will be covered with colour.

The priest thought the statue **warp/weep** through its protective **wrap** and stared in disbelief.

Sentences used in Chapters 3 and 4 Experiments

(Preview conditions used in Chapter 3 Experiment: TL2, TL13, TL23, SL12, SL13, SL23)

The blonde girl spotted the brown monkey in the zoo.

(omnkey, nomkey, mnokey, ecnkey, sovkey, mrekey)

Tom got an appointment with the nice doctor in the hospital.

(odctor , codtor, dcotor, etctor, nobtor, dmator)

Peter put clothes in the laundry basket ready for washing.

(absket, sabket, bsaket, elsket, natket, bviket)

Paul and his friends go to the sports centre twice a week.

(ecntre, nectre, cnetre, omntre, sevtre, cmatre)

You can find nice fruit in the local market on Tuesdays.

(amrket, ramket, mraket, ovrket, vanket, mveket)

The men followed the rules of the young captain on the ship.

(acptain, pactain, cpatain, imptain, gartain, cgotain)

Kelly always chooses her lucky number to play the lottery.

(unmber, munber, nmuber, acmber, rusber, nseber)

The man was in grave danger as he climbed the mountain.

(adnger, nadger, dnager, alnger, cafger, dveger)

We saw a large badger when we went for a walk last night.

(abdger, dabger, bdager, eldger, lafger, bfoger)

We did not stay much longer than you at the birthday party.

(olnger, nolger, lnoger, itnger, mofger, lcager)

Alex helped the animal rescue centre with his pocket money.

(erscue, sercue, rsecue, avscue, cercue, rmucue)

The teacher only found one small mistake in my homework.

(imstake, simtake, msitake, unstake, rictake, mnutake)

My sister saw the kind dentist today so she was not scared.

(edntist , nedtist, dnetist, ilntist, ceftist, dcatist)

A pet dog or cat can be great company for older people.

(ocmpany, mocpany, cmopany, ermpany, norpany, cvapany)

I like the grey donkey that lives in a field behind my house.

(odnkey, nodkey, dnokey, etnkey, cofkey, dmakey)

The singer became very nervous after making a mistake.

(enrvous, renvous, nrevous, imrvous, cesvous, ncovous)

Lisa was allowed to feed the young dolphin at the zoo.

(odlphin, lodphin, dlophin, etlphin, tobphin, dtaphin)

I saw a film about a tiny little penguin on the tv today.

(epnguin, nepguin, pneguin, eqnguin, mejguin, pcoguin)

Daniel drew a picture with a green pencil for his grandma.

(epncil, nepcil, pnecil, egncil, segcil, pmatil)

Mum put a small candle on a cupcake for dad's birthday.

(acndle , nacdle, cnadle, imndle, vasket, cvedle)

My ears were sore after the really loud concert last night.

(ocncert, noccert, cnocert, erncert, voscert, cmacer)

My aunt Mary is the most <u>distant</u> relative in my family.

(idstan, sidtant, dsitant, utstant, viltant, dnutant)

The girl put in her contact <u>lenses</u> to go out with her friends.

(elnses, nelses, lneses, abnses, mebses, lcoses)

The letter was stuck with a large <u>magnet</u> on our fridge door.

(amgnet, gamnet, mganet, ovgnet, pasnet, mpunet)

My uncle has a short <u>temper</u> and shouts when I'm naughty.

(etmper, metper, tmeper, admper, celper, tcaper)

James got a special <u>mention</u> in assembly on his birthday.

(emntion, nemtion, mnetion, orntion, vestion, mcotion)

Sue got her hair cut shorter than <u>normal</u> and it looked nice.

(onrmal, ronmal, nromal, usrmal, cosmal, nvemal)

My family always goes on a long <u>camping</u> trip every summer.

(acmping, macping, cmaping, unmping, narping, cnoping)

In winter we have <u>central</u> heating to keep our house warm.

(ecntral, nectral, cnetral, omntral, sevtral, cmatral)

There is a huge <u>temple</u> in the city where people go to pray.

(etmple, metple, tmeple, admple, celple, tvaple)

The baby felt asleep after many <u>tender</u> kisses from his mum.

(etnder, netder, tneder, odnder, sebder, tcoder)

I found a little *reptile* hiding under a stone in our garden.

(erptile, pertile, rpetile, avptile, megtile, rgotile)

The clothes that people wore last century look really funny.

(ecntury, nectury, cnetury, omntury, vestury, cmatury)

I put lots of silver tinsel on the Christmas tree this year.

(itnsel, nitsel, tnisel, olnsel, sibsel, tvesel)

I made a lovely pie with pastry and apples this afternoon.

(apstry, saptry, psatry, eqstry, ragtry, pvitry)

Kate's clothes were in an awful tangle on the bedroom floor.

(atngle, natgle, tnagle, elngle, madgle, tcogle)

The boys all had spicy mustard with their burgers today.

(umstard, sumtard, msutard, icstard, ructard, mvitard)

I woke up and heard the clear tinkle of a bell somewhere.

(itnkle, nitkle, tnikle, olnkle, midkle, tvekle)

The nurse had to put a fresh bandage on his leg after three weeks.

(abndage, nabdage, bnadage, elndage, cafdage, bvedage)

The oil was stored in a huge tanker until it was needed.

(atnker, natker, tnaker, elnker, ralker, tcoker)

Beth went to the cinema to see the latest vampire film.

(avmpire, mavpire, vmapire, ermpire, nacpire, vnopire)

My football team's mascot is a giant teddy bear in uniform.

(amscot, samcot, msacot, ovscot, ravcot, mvicot)

The little boy is a real rascal because he plays jokes on people.

(arscal, sacral, rsacal, imscal, camcal, rmucal)

My neighbours planted a small conker tree in their garden.

(ocnker, nocker, cnoker, ernker, vosker, cveker)

The potter had very nimble hands and made a lovely vase.

(inmble, minble, nmible, acmble, risble, ncoble)

I heard the wind blowing through the tall bamboo plants.

(abmboo, mabboo, bmaboo, elmboo, nalboo, bneboo)

The new building has window ledges that are painted blue.

(eldges, delges, ldeges, abdges, betges, ltiges)

Tom cried when his little finger got caught in the door.

(ifnger, nifger, fniger, ubnger, cifger, fveger)

I was given a plain biscuit but I prefer chocolate ones.

(ibscuit, sibcuit, bsicuit, udscuit, nitcuit, bnucuit)

Mum poured lots of yellow custard on my pudding at tea time.

(ucstard, suctard, csutard, ivstard, rumtard, cmotard)

The horse jumped six white fences and won the competition.

(efnces, nefces, fneces, olnces, dejces, fcoces)

We went to buy meat from the nice butcher across the street.

(ubtcher, tubcher, btucher, iftcher, dufcher, bdecher)

The secretary left a thick bundle of letters on the table.

(ubndle, nubdle, bnudle, ifndle, cufdle, bmodle)

The ambulance took the hurt victim quickly to the hospital.

(ivctim, civtim, vcitim, umctim, nimtim, vmutim)

The front bumper fell off dad's car today and he was cross.

(ubmper, mubper, bmuper, ifmper, nulper, bciper)

The boss bought a new dumper truck for the building project.

(udmper, mudper, dmuper, ibmper, culper, dciper)

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