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Parafoveal Preprocessing of Word Initial Trigrams During Reading in Adults and Children

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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 preprocessing 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 Positions 1 and 2 (*acptain-imptain*); 1 and 3 (*pactain-gartain*), and 2 and 3 (*cpatain-cgotain*). Results showed a transposed letter effect (TLE) in Position 13 for gaze duration in the pretarget word; and TLE in Positions 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.

Keywords: letter position encoding, parafoveal preview, eye movements, children

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 preprocessing of letter identity and position information in a word's initial trigram by children and adults during silent sentence reading was explored.

Parafoveal Preprocessing in Children and Adults

Research in parafoveal preprocessing 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 and 4 letters to the left and 6 or 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 to 4 letter spaces to the left of fixation and 11 letters to the right; while the span was 3 to 4 letters spaces to the left and 14 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, 6th 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 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 preprocessed in the parafovea. A large body of evidence has showed that skilled adult readers preprocess information regarding word spacing (Epelboim, Booth, Ashkenazy, Taleghani, & Steinman, 1997; Johnson & Eisler, 2012; Johnson et al., 2007; Malt & Seamon, 1978; McConkie & Rayner, 1975; Morris, Rayner, & Pollatsek, 1990; Perea & Acha, 2009a; Pollatsek & Rayner, 1982; Rayner, Fischer, & Pollatsek, 1998;

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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, or 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 Finnish; 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 with adults, they do preprocess information from the word to the right of fixation. In the present study, the boundary paradigm was used to investigate how preprocessing of letter identity and position information within a word's initial trigram affects lexical processing in children compared with adults.

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 to select the appropriate lexical candidate (e.g., 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 that 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 with 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; Forster, 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, Mallouh, & Carreiras, 2010; Perea, Duñabeitia, & Carreiras, 2008; Perea & Pérez, 2009; Perea, Winskel, & Ratitamkul, 2012; Schoonbaert & Grainger, 2004; Taft & Van 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.

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, 2003a).

Newer models of visual word recognition, such as the SOLAR model (Davis, 1999, 2010); the Open Bigram model (Grainger & van Heuven, 2003; Grainger, Granier, Farioli, 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 nonadjacent pairs of letters) that form the word are CA, AL, LM, CL, CM, and AM In both models, adjacent bigrams are more activated than nonadjacent 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 that 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).

Internal Versus 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 with 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 (Johnson, 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 (Experiment 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 nonsignificant, 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, because of 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.

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 with 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 (1975) 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, 2003; Castles et al., 2007). More important, 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 with substituted) letters was found to be greater for 7–9 years old readers than for 10 to 11 years old children or adult (no differences were found between 10 and 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, 2007; Perfetti & Hart, 2001, 2002). 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 because of the reduced requirement for a well-specified representation of the orthographic forms of words. Specifically, because beginning readers only recognize 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 to accurately distinguish between orthographically similar words and to correctly identify the input letter string (see also Share, 1995). 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 with more skilled readers, and would also explain why factors such as vocabulary size, word length and neighbor density also modulate the magnitude of the transposed letter effect (Acha & Perea, 2008b; Castles, Davis, & Letcher, 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).

Grainger and Ziegler's (2011) Model

In Grainger and Ziegler's (2011) model, 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 (a) directly onto semantic representations or (b) onto sublexical morphological and phonological representations that 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 preexisting phonological and morphological sublexical representations because these require the encoding of specific letter position information (note that a number of studies have demonstrated prelexical 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, multiletter graphemes (e.g., sh, th, and ph) and morphemes (e.g., ing, er, and 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 pseudohomophone 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 preprocessing 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, 2007; Perfetti & Hart, 2001, 2002), 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) to discriminate between words (see Castles et al., 2007; Castles et al., 1999), resulting in greater inhibitory transposed letter priming effects in skilled readers when the primes are words (Andrews & 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; Gómez et al., 2008; Grainger et al., 2006; Whitney, 2001). 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).

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, 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 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 experiment, parafoveal preprocessing 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: (a) whether a word's initial letters (e.g., letters 1 and 2) are encoded less flexibly than internal letters (letters 2 and 3); (b) whether such processing operates over individual letters (1 and 2 and 1 and 3 conditions will be similar), or over bigrams (no differences between 1 and 2 and 2 and 3 conditions), such that either the first letter or the first bigram of a word is crucial for the identification of that word because of its role as an access unit; and (c) whether such processing occurs differentially in children compared with skilled adult readers. To examine these issues, the boundary paradigm was used 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 and 2 vs. 1 and 3 vs. 2 and 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 with 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 because of 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 and 2 and 2 and 3 but not in 1 and 3. This latter possibility would indicate that relative letter position information is extracted from the parafovea, for example, 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 Positions 1 and 2 should be of a smaller magnitude than for Position 2 and 3 because of its special role as lexical access unit (Whitney, 2001). The Open Bigram model does not make this distinction (Grainger et al., 2006).

More important, 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 pretarget 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 with adults (Blythe & Joseph, 2011). Second, we predicted that children would have their shortest reading times in the identity condition compared with 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 Häikiö et al., 2010; Rayner, 1986; 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 and 3). Finally, with respect to initial letter manipulations (1 and 2 and 1 and 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 and 2 but not 1 and 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.

Method

Participants

In total, 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 preprocessing information from the word to the right of fixation (Häikiö et al., 2009, 2010; Rayner, 1986). 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, prescreening 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 afterward. University students received course credits as a reward for participating.

Apparatus

The sentences were presented on a 21-inch CRT monitor, set at a refresh rate of 120 Hz with a 1,024 × 768 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 gray 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 to minimize head movements. The spatial resolution of the eye tracker was 0.05°, and the sampling rate was 2,000 Hz. Word reading, pseudoword decoding and reading comprehension for each participant were assessed using the WIAT-II (Wechsler, 2005).

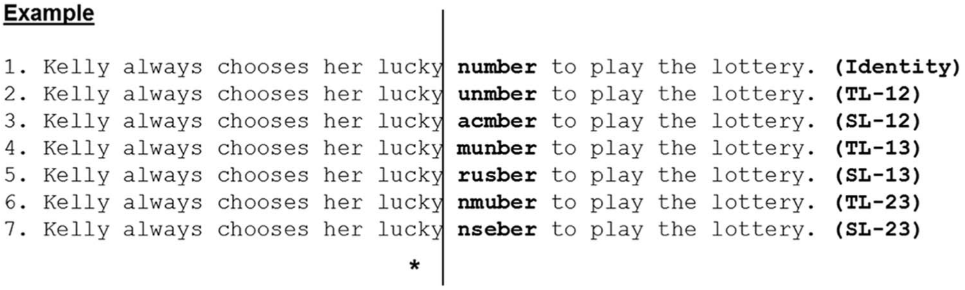
Material and Design

Fifty-six experimental sentences containing a 6–7 letter target word were specially constructed. Target words (nouns or adjectives) were bisyllabic with a consonant-vowel-consonant (CVC) structure for the initial trigram, which was within the same syllabic unit (e.g., *captain*). These target words had fewer than three orthographic neighbors, 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 3 and 276 per million using child frequency counts (*M* = 37, *SD* = 53; Children's Printed Word Database, Masterson, Dixon, Stuart, Lovejoy, & Lovejoy, 2003) and in a range between 0.61 and 3,483 per million using adult frequency counts (*M* = 179, *SD* = 559; English Lexicon Project Database; HAL corpus, Balota et al., 2007). Pretarget words were mainly adjectives between 3 and 7 letters long (M = 5).

Seven parafoveal preview conditions were generated for each target word (see the Appendix). 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: 1 and 2 (12; *acptain* vs. *imptain*); 1 and 3 (13; *pactain* vs. *gartain*); or 2 and 3 (23; *cpatain* vs. *cgotain*; see Figure 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).

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 prescreening procedure. Two sentences were created for each target word to be rated (112 sentences), 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 prescreening 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.



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)**

*

Figure 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.

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 or she reported noticing more than three changes. The experiment lasted about 40 min.

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 preboundary (pretarget) word, or when the display change was not completed until more than 10 ms after fixation onset on the postboundary (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 preboundary word[1] was skipped were not included in the analyses. These procedures resulted in a final data set of 3,619 fixations (81.5% of the data). These data were log transformed for analysis.

Data were analyzed by means of linear mixed effects (lme) modeling 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 analyzed with two lme models. We initially specified a full random structure for subjects and items, to avoid being too anticonservative (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, and 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 *SE*s that we obtained reflect, therefore, both subject and item variability (Baayen, Davidson, & Bates, 2008). Predictor variables were categorical, and were not centered. Following standard conventions, effects were considered significant when $t > 2$. 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, and SL23) compared with 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 =

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[1] The pretarget word was always a 4-6 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 pretarget word was not skipped were included in the analyses; thus, it is likely that the initial trigram was processed parafoveally when the pretarget word was fixated.

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.

Pretarget Word

First, in Model 1, for the pretarget word, only the comparison between adults and children was significant in single, first fixation and gaze duration (see Table 1 for coefficients, *SE*s, and *t*-values), showing that children spent more time looking at the pretarget word than adults when the identity preview was presented in the parafovea (see Table 2 for means and *SD*s). None of the other comparisons reached significance. This finding is consistent with other studies investigating eye movement behavior during reading, which show that children's fixations are longer on words than adults (see Blythe & Joseph, 2011 for a review).

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 pretarget words than adults (see Table 3 for coefficients, *SE*s, and *t*-values). There was a main effect of Position for single fixation duration only, such that the pretarget word received longer reading times when 23-previews were presented in the parafovea compared with 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 pretarget word received also longer reading times when 23-previews were presented in the parafovea compared with 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 with 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 pretarget 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 pretarget word were longer for SL13 previews compared with TL13 previews (see Figure 2). This effect occurred for both adults and children. Thus, at the pretarget 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 because of its greater similarity with its base words 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). 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 pretarget 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 pretarget 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 that were independent participant samples, and that there was no reliable interactive effect with group.

Table 1

Model 1: Lmer (ldepvar ~ Group ∗ Condition + (1\pp) + (1\stim), data = Datafile) for Single, First Fixation, and Gaze Duration in the Pretarget Word

	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	.03	165.0	5.22–5.34	5.27	.03	187.4	5.21–5.32	5.32	.03	156.7	5.26–5.39
Adults, Children	.27	.05	5.7	.18–.36	.22	.04	5.8	.15–.29	.36	.04	8.1	.28–.45
Adult, TL12	.03	.03	1.2	−.02–.10	.03	.03	1.1	−.02–.08	.02	.03	.7	−.04–.09
Adult, TL13	.02	.03	.7	−.04–.08	.01	.03	.3	−.04–.06	−.01	.03	−.3	−.07–.06
Adult, TL23	.02	.03	.7	−.04–.08	.02	.03	.8	−.03–.08	.02	.03	.7	−.04–.09
Adult, SL12	.03	.03	.8	−.03–.09	.02	.03	.8	−.03–.08	.02	.03	.6	−.05–.08
Adults, SL13	.04	.03	1.2	−.02–.10	.01	.03	.4	−.04–.07	.04	.03	1.1	−.03–.10
Adult, SL23	.05	.03	1.5	−.01–.11	.03	.03	1.0	−.03–.08	.03	.03	.9	−.03–.10
Children ∗ TL12	.00	.05	.0	−.10–.10	−.05	.04	−1.4	−.13–.02	−.05	.05	−1.0	−.14–.04
Children ∗ TL13	−.07	.05	−1.3	−.17–.03	−.03	.04	−.9	−.11–.04	−.07	.05	−1.5	−.16–.02
Children ∗ TL23	.01	.05	.9	−.09–.11	−.00	.04	−.1	−.08–.07	−.01	.05	−.3	−.10–.08
Children ∗ SL12	−.10	.05	−1.8	−.20–.00	−.00	.04	−.9	−.11–.04	−.03	.05	−1.1	−.14–.04
Children ∗ SL13	−.10	.05	−1.9	−.20–.00	.00	.04	.1	−.07–.08	−.03	.05	−.7	−.12–.06
Children ∗ SL23	−.02	.05	−.4	−.13–.08	−.03	.04	−.7	−.10–.05	−.05	.05	−1.1	−.14–.04

Note. b = regression coefficient; t = test statistic (b/SE); CI = confidence intervals (2.5% to 97.5%).

Table 2
Means (SDs) in Milliseconds Per Condition in Each Eye Movement Measure in the Pretarget 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)

Target Word

In Model 1, similar to the pretarget word, the comparison between adults and children for the identity condition was significant in all the dependent variables (see Table 4 for coefficients, *SE*s, and *t*-values), showing that children spent more time looking at the target word than adults (see Table 5 for means and *SD*s).

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.[2] 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 6).

In Model 2, and similar to the effects we observed for the pretarget word, the comparison between adults and children was significant in all the dependent variables (see Table 6 for coefficients, *SE*s, and *t*-values), showing that children spent more time looking at the target word than adults (see Table 5).

With respect to letter position, those previews with manipulated letters in Position 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 nonadjacent 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 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 three-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

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[2] 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 analysis of variances (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.

Table 3
Model 2: Lmer (ldepvar ~ Group ∗ Type ∗ Position + (1\pp) + (1\stim), data = Datafile); With Additional Contrasts Comparing 12-Previews and 23- Previews for Single, First Fixation, and Gaze Duration in the Pretarget Word

	Single fixation duration				First fixation duration				Gaze duration			
	b	*SE*	*t*	CI	b	*SE*	*t*	CI	b	*SE*	*t*	CI
Model 2												
Intercept	5.42	.02	271.6	5.38–5.46	5.39	.02	323.7	5.35–5.42	5.51	.02	268.8	5.46–5.55
Group	.22	.03	6.7	.16–.28	.19	.03	6.9	.14–.25	.32	.03	9.8	.26–.38
Type	−.02	.01	−1.1	−.05–.01	.00	.01	.5	−.02–.03	.15	.01	1.1	−.01–.04
Position (12–13)	−.02	.02	−1.0	−.05–.02	−.00	.01	−.2	−.03–.02	−.01	.02	−.0	−.04–.02
Position (13–23)	.04	.02	2.3	.01–.08	.01	.01	1.1	−.01–.04	.02	.02	1.3	−.01–.05
Group × Type	−.06	.03	−1.9	−.11–.00	.01	.02	.6	−.03–.05	−.00	.03	−.0	−.05–.05
Group × Position (12–13)	−.03	.04	−.9	−.10–.04	.03	.03	1.0	−.03–.08	−.00	.03	−.1	−.07–.06
Group × Position (13–23)	.07	.04	2.0	.00–.14	.00	.03	.0	−.05–.05	.02	.03	.6	−.04–.08
Type × Position (12–13)	.06	.04	1.8	−.01–.13	.02	.03	.8	−.03–.07	.07	.03	2.1	.00–.13
Type × Position (13–12)	.01	.04	.3	−.06–.08	−.03	.03	−1.1	−.08–.02	−.07	.03	−2.3	−.14–(−.01)
Group × Type × Position (12–13)	.07	.07	.9	−.07–.21	.02	.05	.4	−.09–.12	.04	.06	.6	−.09–.17
Group × Type × Position (13–23)	.00	.07	.0	−.14–.14	−.06	.05	−1.1	−.17–.04	−.07	.07	−1.0	−.20–.06
Contrasts												
Position (12–23)	−.02	.02	−1.4	−.06–.01	−.01	.02	.6	−.04–.01	−.01	.02	−.9	−.05–.02
Group × Position (12–23)	−.04	.04	−1.2	−.11–.03	−.03	.03	−1.0	−.08–.25	−.02	.03	−.5	−.08–.05
Type × Position (12–23)	−.07	.04	−2.0	−.14–.00	.01	.03	.3	−.04–.06	.01	.03	.2	−.06–.07
Group × Type × Position (12–23)	−.06	.07	−.8	−.20–.08	.04	.05	.0	−.06–.15	.03	.06	.4	−.10–.16

Note. b = regression coefficient; *t* = test statistic (b/*SE*); CI = confidence intervals (2.5% to 97.5%).

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 because of 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 because of that model's use of individual letter representations. Alternatively, our pattern of results might be explained as being because of 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 Positions 12, 13, and 23 ($p < .000$). 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), 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.

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.

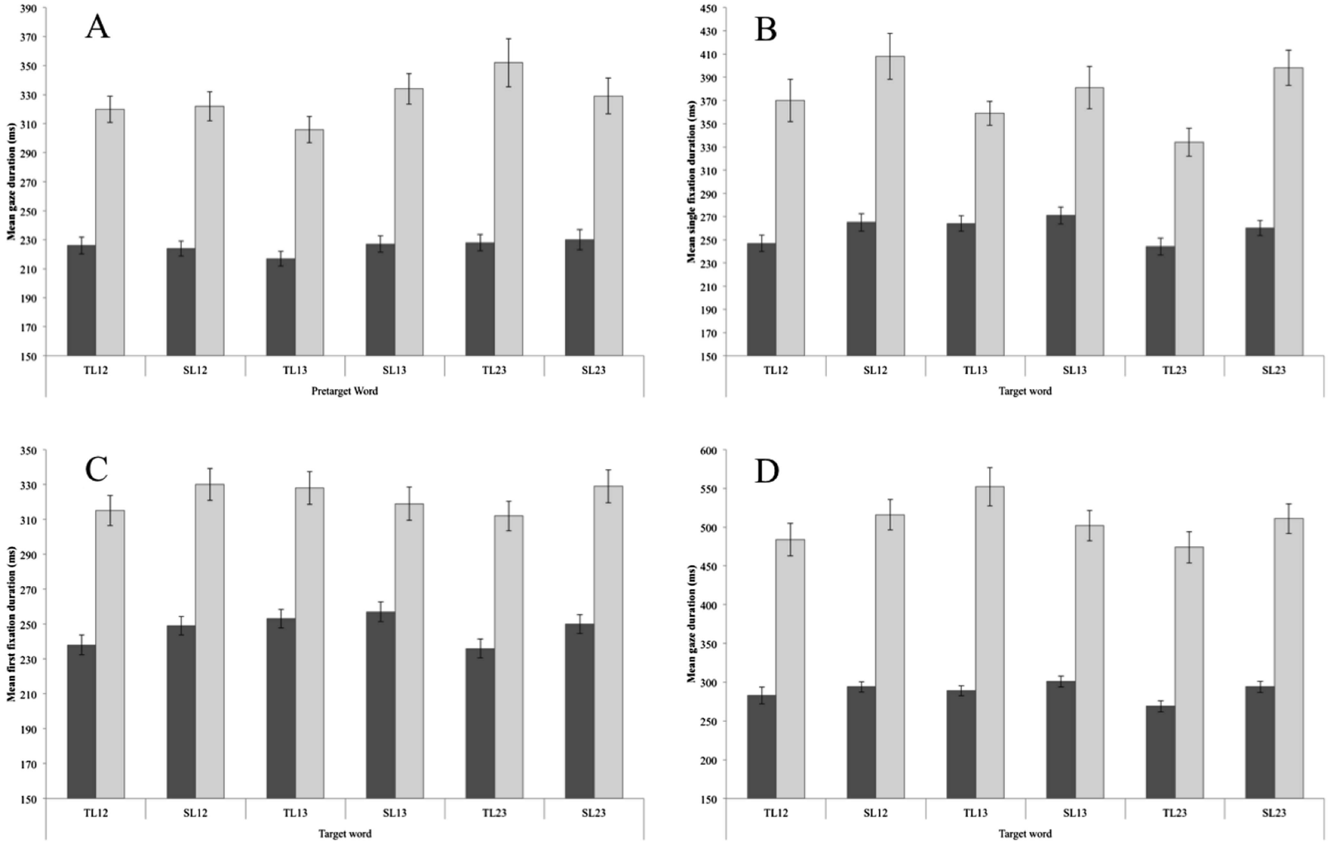

Figure 2. Reading time data for the pretarget and target words, showing the effects of Group (adults vs. children), Position (12 vs. 13 vs. 23), and Type (TL vs. SL). Pale gray bars represent data from children, and dark gray bars represent data from adults. Panel (A) shows gaze duration data on the pretarget 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 *SE* for each condition.

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 behavior during reading, and how these behavioral 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.

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, Bertam, 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 behavior, may be associated with developmental changes in the quality of cognitive lexical representations as per Perfetti's Lexical Quality Hypothesis (Perfetti, 2007; Perfetti & Hart, 2001, 2002). 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 (e.g., 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

Table 4
*Model 1: Lmer (depvar ~ Group * Condition + (1\pp) + (1\stim), data = Datafile) for Single, First Fixation, and Gaze Duration in the Target Word*

	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	.04	148.4	5.33–5.47	5.36	.03	159.6	5.30–5.43	5.47	.04	120.3	5.38–5.55
Adults, Children	.31	.05	5.8	.21–.42	.22	.04	5.0	.14–.31	.50	.06	8.6	.38–.61
Adult, TL12	.05	.03	1.4	−.02–.11	.04	.03	1.1	−.03–.10	.07	.04	1.9	−.00–.14
Adult, TL13	.12	.03	3.6	.06–.19	.11	.03	3.3	.04–.18	.13	.04	3.6	.06–.20
Adult, TL23	.02	.03	.7	−.04–.09	.03	.03	1.0	−.03–.10	.03	.04	.8	−.04–.10
Adult, SL12	.14	.03	4.0	.07–.20	.09	.03	2.8	.03–.16	.14	.04	4.1	.07–.21
Adults, SL13	.16	.03	4.5	.09–.23	.13	.03	3.7	.06–.19	.16	.04	4.4	.09–.23
Adult, SL23	.11	.03	3.3	.05–.18	.10	.03	3.0	.03–.17	.15	.04	4.0	.07–.22
Children*TL12	.05	.06	.8	−.07–.16	.02	.05	.4	−.07–.11	−.02	.05	−.3	−.11–.08
Children*TL13	.06	.06	1.0	−.06–.18	−.00	.05	−.1	−.09–.08	.04	.05	.8	−.06–.14
Children*TL23	.06	.06	1.0	−.05–.17	.03	.05	.7	−.06–.12	−.00	.05	−.0	−.10–.09
Children*SL12	.14	.06	2.2	.01–.26	.01	.05	.3	−.07–.10	−.02	.05	−.4	−.11–.08
Children*SL13	.01	.06	.1	−.11–.13	−.05	.05	−1.1	−.14–.04	−.05	.05	−1.0	−.15–.04
Children*SL23	.12	.06	2.0	.00–.23	.00	.05	.1	−.09–.10	−.03	.05	−.5	−.12–.07

Note. b = regression coefficient; *t* = test statistic (b/*SE*); CI. = confidence intervals (2.5% to 97.5%).

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.

Transposed Letter Effects in Parafoveal Preview

There were three key findings from the present study: (a) both adults and children were able to preprocess information regarding the identities of letters within the initial trigram of the parafoveal word; (b) there was an early transposed letter effect in Positions 13, such that a transposition of these letters resulted in shorter reading times than if they were substituted; and (c) a slightly later transposed letter effect in Positions 12 and 23. 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 preprocess 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 with the identity condition. This basic finding confirms that, as predicted on the basis of the published literature, skilled adult readers are preprocessing 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 preprocessing during reading, and how such a skill develops with age and reading skill. More important, some studies have indicated that the perceptual span is reduced in children compared with adults (Häikiö et al., 2009; Rayner, 1986; Sperlich et al., 2015). Specifically, when using the moving window technique, children aged 7–9 years old are sensitive to information presented up to 11 letter spaces to the right of fixation, in comparison to 14 letter spaces in adults. Recall that our child participants were 8–9 years old, and the pretarget words were 4–5 letters long; thus, the target word's initial trigram should always have fallen within the children's perceptual span during fixations on the pretarget word (given that participants were prescreened 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 preprocess information from the initial trigram, and we examined specifically whether they were able to preprocess orthographic information. As predicted, we found that children were sensitive to changes in letter position information before the target word was

Table 5
Means (SDs) 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)

Table 6

*Model 2: Lmer (ldepvar ~ Group * Type * Position + (1\pp) + (1\stim), data = Datafile)); With Additional Contrasts Comparing 12-Previews and 23- Previews for Single, First Fixation, and Gaze Duration in the Target Word*

	Single fixation duration				First fixation duration				Gaze duration			
	b	*SE*	*t*	CI	b	*SE*	*t*	CI	b	*SE*	*t*	CI
Model 2												
Intercept	5.69	.02	242.2	5.65–5.74	5.56	.02	292.7	5.52–5.60	5.82	.03	195.5	5.76–5.88
Group	.39	.04	9.7	.31–.47	.23	.03	6.6	.16–.30	.48	.05	10.1	.39–.58
Type	.09	.02	4.9	.05–.13	.03	.01	2.5	.01–.06	.06	.01	4.0	.03–.08
Position (12–13)	.02	.02	.7	−.03–.06	.03	.02	1.8	−.00–.06	.04	.02	2.5	.01–.08
Position (13–23)	−.04	.02	−2.0	−.09–.00	−.03	.02	−1.6	−.06–.01	−.06	.02	−3.4	−.09–.02
Group × Type	.04	.04	1.0	−.3–.11	−.03	.03	−1.0	−.08–.02	−.04	.03	−1.4	−.09–.01
Group × Position (12–13)	−.05	.05	−1.1	−.14–.04	−.05	.03	−1.4	−.11–.02	.01	.03	.4	−.05–.08
Group × Position (13–23)	.05	.04	1.2	−.03–.13	.05	.03	1.5	−.02–.11	−.01	.03	−2.4	−.08–.06
Type × Position (12–13)	−.13	.05	−2.9	−.22–(−.04)	−.06	.03	−1.9	−.13–.00	−.09	.03	−2.8	−.16–(−.03)
Type × Position (13–12)	.11	.04	2.7	.03–.20	.06	.03	1.9	−.00–.13	.12	.03	3.5	.05–.19
Group × Type × Position (12–13)	−.15	.09	−1.6	−.34–.03	−.04	.06	−.7	−.17–.08	−.09	.07	−1.4	−.23–.04
Group × Type × Position (13–23)	.12	.09	1.4	−.05–.29	.02	.07	.3	−.11–.15	.06	.07	.9	−.07–.20
Contrasts												
Position (12–23)	.03	.02	1.2	−.02–.07	−.00	.02	−.2	−.03–.03	.02	.02	1.0	−.02–.05
Group × Position (12–23)	.00	.04	.1	−.08–.09	−.00	.03	−.0	−.07–.06	−.00	.03	−.1	−.07–.06
Type × Position (12–23)	.00	.04	.1	−.08–.09	−.00	.03	−.0	−.07–.06	−.03	.03	−.8	−.09–.04
Group × Type × Position (12–23)	−.00	.09	.0	−.17–.17	.02	.07	.4	−.10–.15	.02	.07	.4	−.11–.16

Note. b = regression coefficient; *t* = test statistic (b/*SE*); CI = confidence intervals (2.5% to 97.5%).

directly fixated, demonstrating that they were preprocessing orthographic information from the parafovea as we know that adults do.

The early processing of letters 1 and 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 with manipulations of letters 12 and 23. Specifically, there was a TLE for Position 13 during fixations on the pretarget word, such that reading times were longer when the preview was a SL13 nonword compared with 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 the Appendix, 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 preprocessing occurs because of its ortho-

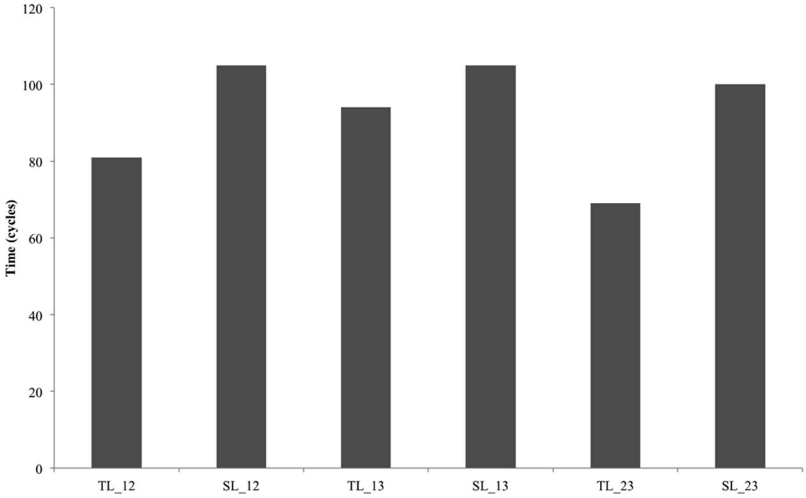

Figure 3. Output for the masked priming lexical-decision task simulation run in the spatial coding model (SCM) (Davis, 2010), across the six experimental conditions.

graphic 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 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 pretarget 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, Duñabeitia, & Molinaro, 2009; Carreiras, Gillon-Dowens, Vergara-Martinez & Perea, 2009; Carreiras & Price, 2008; Carreiras, Vergara-Martinez, & Perea, 2007, 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., 2006; 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 pretarget 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.[3] 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 preprocessing 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 pretarget 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. While we predicted a basic TLE in children's fixation times on the target word, it is remarkable that 8- to 9-year-old children could encode letter position information so early in lexical processing during parafoveal preview, that it influenced fixation times on the pretarget 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 (that 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 word-reading 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 behavior during reading are similar to adult's eye movement behavior at the age of 11 years (see Blythe & Joseph, 2011 for a review).

Independent parafoveal preprocessing 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 preprocessed 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).

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[3] This finding contrasts with the results from Johnson (2007), who showed that there were no processing differences between consonants and vowels in the parafovea during sentence reading. This could, however, be a consequence of the distance between the point of fixation on the pretarget 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.

To confirm this, we specifically compared reading times for transposed versus 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 while 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 (a) the unit of representation (letters vs. bigrams); and (b) 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. 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 preprocessing, 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 with 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 preprocessing. 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 preprocessing 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. 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) 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 preprocessing. Second, through the capitalization of the first letter of all nouns in German (all target words were capitalized nouns in Tiffin-Richards and Schroeder's study). It seems feasible that a capitalized 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 capitalized 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 5th 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 3rd 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 with adults (Perfetti, 2007; Perfetti & Hart, 2001, 2002), 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 behavior during reading must reflect ongoing developmental changes in aspects of reading that occur at a higher level than orthographic encoding (Luke, Henderson, & Ferreira, in press). This is consistent with the Lexical Quality Hypothesis by Perfetti (2007; Perfetti & Hart, 2001, 2002).

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. Finally, 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.

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Appendix

Material

Experimental sentences and preview conditions (TL12, TL13, TL23, SL12, SL13, and 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 *center* 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* center 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 gray *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 *distant* relative in my family.
(*idstan, sidtant, dsitant, utstant, viltant, dnutant*)

The girl put in her contact *lenses* to go out with her friends.
(*elnses, nelses, lneses, abnses, mebses, lcoses*)

The letter was stuck with a large *magnet* on our fridge door.
(*amgnet, gamnet, mganet, ovgnet, pasnet, mpunet*)

My uncle has a short *temper* and shouts when I'm naughty.
(*etmper, metper, tmeper, admper, celper, tcaper*)

James got a special *mention* in assembly on his birthday.
(*emntion, nemtion, mnetion, orntion, vestion, mcotion*)

Sue got her hair cut shorter than *normal* and it looked nice.
(*onrmal, ronmal, nromal, usrmal, cosmal, nvemal*)

My family always goes on a long *camping* trip every summer.
(*acmping, macping, cmaping, unmping, narping, cnoping*)

In winter we have *central* heating to keep our house warm.
(*ecntral, nectral, cnetral, omntral, sevtral, cmatral*)

There is a huge *temple* in the city where people go to pray.
(*etmple, metple, tmeple, admple, celple, tvaple*)

The baby felt asleep after many *tender* 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 neighbors 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*)

(*Appendix continues*)

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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