Letter position coding in printed word perception: Effects of repeated and transposed letters

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We report four experiments investigating the effects of repeated and transposed letters in orthographic processing. Orthographically related primes were formed by removing one letter from the target word, by transposing two adjacent letters, or by replacing two adjacent letters with different letters. Robust masked priming in a lexical decision task was found for primes formed by removing a single letter (e.g., mirce-MIRACLE), and this was not influenced by whether or not the prime contained a letter repetition (e.g., balace vs. balnce as a prime for BALANCE). Target words containing a repeated letter tended to be harder to respond to than words without a letter repetition, but the nonwords formed by removing a repeated letter (e.g., BALNCE) were no harder to reject than nonwords formed by removing a non-repeated letter (e.g., MIRCLE, BALACE). Significant transposition priming effects were found for 7-letter words (e.g., service-SERVICE), and these priming effects did not vary as a function of the position of the transposition (initial, final, or inner letter pair). Priming effects disappeared when primes were formed by replacing the two transposed letters with different letters (e.g., sedlice-SERVICE), and five-letter words only showed priming effects with inner letter transpositions (e.g.,

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We present a revised “open-bigram” scheme for letter position coding that accounts for these data.

If there is one aspect of sublexical processing in visual word recognition for which there exists a general consensus among researchers working on the topic, this must be the role of individual letters. It is generally assumed that the recognition of a printed word during reading is mediated by some minimal orthographic processing that involves the word’s component letters, at least in languages that use an alphabetic orthography. Although there is some evidence for the operation of more holistic information, such as word shape or contour (Perea & Rosa, 2002), this is generally considered as supplementary to letter-based orthographic processing. In the vast majority of accounts of visual word recognition, the individual letter is thought to be the unit that provides information input to more complex sublexical and lexical processes, such as phonological and morphological processing. More precisely, the input is generally thought to be an ordered set of letter identities, but exactly how the order information is computed is still not clearly understood.

The present study provides a modest contribution to this less-investigated component of orthographic processing. We first describe current theoretical positions concerning how letter position information is processed during printed word perception. Then we present some recent orthographic priming data that limit the number of viable possibilities. Then we discuss the case of repeated letters, which is the focus of Experiments 1 and 2. Following Experiment 2, we examine the case of letter transpositions, to be studied in the last two experiments.

LETTER POSITION CODING

Current theoretical approaches to coding the position of letters in a string of letters can be classified into three major kinds: slot-based coding, local context-sensitive coding, and spatial coding. Slot-based coding involves units that code letter identity and position together, such that a given letter is tagged to a specified location in the string. The different possible locations are the slots to which the different letters can be associated. For example, in the interactive activation model of McClelland and Rumelhart (1981), letter strings are processed in parallel by a set of length-dependent, position-specific letter detectors. This means, for example, that there is a processing unit for the letter T as the first letter of a 4-letter word, a different unit for T as the second letter of a 4-letter word, and a different unit for the letter T as the first letter of a 5-letter word. This is the most efficient means of coding letter position information, but efficiency is
bought at great cost: a large number \((n + n - 1 + n - 2 \ldots + 1)\) of duplications of the alphabet are necessary in order to code all positions in letter strings of up to length \(N\).

Relative-position coding can be introduced into slot-based coding schemes by adding anchor points. Letter position is then defined relative to the given anchor point(s). In recent modelling work extending the original interactive activation model (Coltheart, Curtis, Atkins, & Haller, 1993; Jacobs, Rey, Ziegler, & Grainger, 1998) two different relative-position coding schemes have been proposed that adopt one or more anchor points. Coltheart et al. adopted a left-to-right length-independent coding scheme. Letter position is coded relative to the beginning of the string such that the third letter in a 4-letter string is coded as being in the same position as the third letter of a 7-letter string (see also Coltheart, Rastle, Perry, Ziegler, & Langdon, 2001). Jacobs et al. (1998) used the beginning and end points of a letter string as two anchor points for relative-position coding. Thus the following string “BLACK” was coded as \(I = “B”; I + 1 = “L”; I + 2 = “F – 2 = “A”; F – 1 = “C”; F = “K”,\) where \(I\) stands for initial letter and \(F\) for final letter in the string. The major motivation for adopting either of these two coding schemes was to implement a single coding scheme and a single lexicon for words of varying length in an interactive activation model of visual word recognition.

In recent computational models of reading aloud, a more minimalist slot-based coding scheme has been used to deal with monosyllabic words (Harm & Seidenberg, 1999; Plaut, McClelland, Seidenberg, & Patterson, 1996). Three positions are defined relative to the orthographic onset, nucleus, and coda of the word, and letters are assigned to one of these three positions. Such schemes provide a quite accurate means of coding of letter position for word stimuli since there is hardly any ambiguity in the position of a given set of letters assigned to one of these positions (e.g., given T, S, and R assigned to the onset position, there is only one possible order of these letters as the onset of an English monosyllabic word: STR). However, this coding scheme begs the question as to why a normal reader of English does not misinterpret RTSING as STRING? Obviously the order of letters within each position slot needs to be represented. This is the case in the solution adopted by Zorzi, Houghton, and Butterworth (1998). In this scheme, letter position in monosyllabic words is coded relative to the orthographic onset and rime. The authors defined three onset positions (O1, O2, O3) and five rime positions (R1, R2, R3, R4, R5) in order to specify the order of letters within each segment. It should be noted that coding schemes such as these using sub-syllabic structure to code letter location, require a pre-classification of letters as consonants and vowels before position coding can begin.
Finally, the minimalist slot-based scheme (excluding a one-slot scheme which is tantamount to not coding for position at all) was proposed by Shillcock, Ellison, and Monaghan (2000) in their split-fovea model of visual word recognition. Letters are assigned to one of two possible positions: left and right of the point of eye fixation in the word. Letters falling to the left of fixation are sent to the right hemisphere and processed as an unordered set of letters in that position, while letters to the right of fixation are sent to the left hemisphere forming an unordered set of letters in that location. Shillcock et al. (2000) showed that 98.6% of all the words in the CELEX database were uniquely identified by the two sets of unordered letters generated by a central/centre-left split. However, for 4-letter words this figure dropped somewhat, with 4.7% of these words being ambiguous. Shillcock et al. solved this problem by specifying the identity of the first and last letter, thus assigning a special role to exterior letters in orthographic processing. Thus, in this particular version of the split-fovea model, letter identities are in fact assigned to one of four possible positions: first letter, last letter, inner letter left, inner letter right. However, more recent implemented versions of this model (e.g., Shillcock & Monaghan, 2001) have adopted a multiple slot-based coding scheme that provides information about the relative position of letters in the right and left visual hemifields. We will return to this model in the section on relative-position priming.

The inspiration for letter position coding schemes that use local-context comes from the work of Wickelgren (1969) who introduced the concept of a “wickelphone” as a means for encoding phoneme positions in speech. This scheme was adapted by Seidenberg and McClelland (1989) in the form of “wickelgraphs” or letter triples. Thus the word BLACK is coded as an unordered set of letter triples: #BL, BLA, LAC, CK, CK# (where # represents a space). Wickelgraphs code local context in that only information about the relative position of adjacent letters is directly computed. In general, however, a given set of letter triples has only one possible ordering for a given language (e.g., the five wickelgraphs for the word BLACK cannot be re-arranged to form another English word). A more elaborate local-context scheme was proposed by Mozer (1987) in his BLIRNET model. Again, letter triples form the basis of local-context coding in this model, but the scheme is enhanced by the use of what we will refer to as “open-trigrams”. In Mozer’s model such open-trigrams could be formed by inserting a letter between the first and the second, or between the second and the third letter of each letter triple. So the word BLACK contains the letter triple BLA (and other letter triples as above) plus the open trigrams BL_A and B_LA associated with this triple. The underscore signifies that any letter can be inserted in this position. The idea of coding the relative position of non-adjacent letters has been used in two more
recent accounts of letter position coding (Grainger & van Heuven, 2003; Whitney, 2001). In the model of letter position coding proposed by Whitney (2001), we find a clear illustration of how open-bigrams can be used in orthographic processing. In Whitney’s (2001) example, the word CART is coded as the following set of bigrams: CA, CR, CT, AR, AT, RT. Thus bigrams are formed across adjacent and non-adjacent letters in the correct order, the basis of what we refer to as open-bigram coding. In Whitney’s model, the correct bigrams are activated on the basis of position information provided in a locational gradient at the level of letter representations. In this respect Whitney’s model can also be categorised as a spatial coding scheme using an activation gradient to derive letter positions.

The notion of spatial coding was developed by S. Grossberg (e.g., Grossberg, 1978), and forms the basis of two recent accounts of letter position coding: the SERIOL model (Whitney, 2001) and the SOLAR model (Davis, 1999). The relative position of spatially distributed items is coded in terms of their relative activation level. This is best achieved when the items in the list form a monotonically increasing or decreasing set of activation values, referred to as an activation gradient. For the purposes of letter position coding, the activation gradient must form a monotonically decreasing activation function across letter position with the highest value for initial letters and the lowest value for the final letter of the string. Whitney (2001) describes a method for translating acuity-dependent activations into the desired monotonically decreasing gradient. As mentioned above, the SERIOL model transforms relative activation at the letter level to activation of ordered bigram units (open-bigrams).

The starting point for processing in the SOLAR model (Davis, 1999) is a set of letter identities that provide serial, left-to-right input to the orthographic processing system, one letter at a time. Since there is only one node for each letter in the letter identification system, letter repetitions cannot be represented at this level. The SOLAR model handles letter repetitions via a latch-field that mediates between letter input and nodes in the orthographic processing module. The latch-field controls the timing of information transfer from the sequential letter input to the spatial orthographic code. Each letter node is connected to four latch-nodes that represent the maximum number of repetitions of a letter in an English word. In this way different nodes handle repeated letters giving them practically the same status as non-repeated letters. Thus, the word BANANA would be represented in the orthographic processing layer as the nodes B1, A1, N1, A2, N2, and A3, with monotonically decreasing activation levels across these six nodes. Activity in these orthographic input nodes is then fed onto a layer representing sequences
(lists) of letters, that may correspond to whole-words, or to frequently occurring parts of words such as affixes and bound stems.

**RELATIVE-POSITION PRIMING**

The vast majority of the above-mentioned coding schemes fail to account for a now well-established result obtained with the masked priming paradigm. Using a four-field variant of this technique with briefly presented primes and targets, Humphreys, Evett, and Quinlan (1990) investigated orthographic priming by varying the number of letters shared by prime and target and the relative position of letters in primes and targets. We will follow the notation of Humphreys et al. in describing different types of orthographic prime. When no specific example is given, a prime condition is described using the numbered letters of the target (e.g., 12345 for a 5-letter target) to indicate which of the target letters appeared in the prime and in which location they appeared. Letters that are present in the prime stimulus but are not present in the target are indicated by the letter “d” (for different). So the prime 1d3d5 indicates that primes shared the first, third, and fifth letters with targets and had two unrelated letters placed in the second and fourth positions.

One key result reported by Humphreys et al. (1990) involves what they referred to as relative-position priming. In this situation, primes and targets differ in length so that absolute position information changes, while the relative order of letters in primes and targets is maintained. Using the above-mentioned notation for describing orthographic primes, for a 5-letter target (12345), a 5-letter prime stimulus such as 12d45 contains letters that have the same absolute position in prime and target, while a 4-letter prime such as 1245 contains letters that preserve their relative order in prime and target but not their precise length-dependent position. Humphreys et al. (1990, Experiment 4) found significant priming for primes sharing four out of five of the target’s letters in the same relative position (1245) compared with both a cross-position condition (1425) and an outer-letter only condition (1dd5).

More evidence for effects of relative-position priming was provided by Peressotti and Grainger (1999). With 6-letter target words, relative-position primes (1346) produced significant priming compared with unrelated primes (dddd). Inserting filler letters or characters (e.g., 1d34d6, 1-34-6) to provide absolute position information never led to significantly larger priming effects in this study. Violating the relative position of letters across prime and target (e.g., 1436, 6341) cancelled priming effects relative to all different letter primes (dddd). These relative-position priming effects have found further support in some unpublished work from our laboratory (Granier & Grainger, 2004). Using 7-letter
French words, significant priming relative to an all-different letter prime condition was obtained for primes formed by the first, last, and three central letters (13457), but no priming was obtained for primes where the order of the three central letters was reversed (15437), or where the first and last letter were transposed (73451). Using Italian 9-letter stimuli, Pesciarelli, Peressotti, and Grainger (2001) found significant priming for 5-letter primes sharing the first, last, and a combination of three inner letters of target words (e.g., 12349, 16789, 14569, 13579). Finally, Granier and Grainger (2003) compared effects for primes sharing initial letters with 7 and 9-letter targets (12345) compared with primes sharing final letters (34567, 56789). These conditions were found to generate about the same amount of priming, and stronger priming than a condition maintaining both of the target’s outer letters (13457, 14569). It should be noted that this result is particularly damaging for the version of the split-fovea model of letter position coding described in Shillcock et al. (2000), since for example, for a 9-letter word, a 14569 prime correctly assigns all letters to the left and right of a central fixation point, whereas 12345 and 56789 primes clearly do not. However, it remains to be seen whether later versions of this model can accommodate relative-position priming effects. Shillcock and Monaghan (2001) used a staggered presentation technique to simulate the variable viewing positions that are encountered during normal reading. The model is trained to “recognise” the same word at different viewing positions, and given the split-fovea architecture, the hidden units in the model will “learn” to represent the different letter clusters that are formed by a staggered presentation. The shift-invariant mapping that the model learns should allow it to capture priming effects obtained with consecutive letter primes (e.g., 56789), but might run into trouble with priming effects from non-adjacent letter combinations (e.g., 13579).

These relative-position priming effects probably provide the single most constraining set of data for any model of orthographic processing (another critical set of results concerns letter transposition effects, to be summarised in the introduction to Experiment 3). Practically all of the above letter position coding schemes fail to account for these effects. Here we will examine three models that can account for relative-position priming effects. These are Davis’ (1999) SOLAR model, Whitney’s (2001) SERIOL model, and the open-bigram scheme of Grainger and van Heuven (2003). The present study provides a further test of these specific coding schemes. One point on which these schemes differ, concerns the presence or absence of positional biases in orthographic priming. This is examined in the second part of the study where we focus on the role of transposed letters. The first part of the present study (Experiments 1 and 2) focuses on the role of repeated letters in orthographic processing.
Repeated letters are problematic for any relative position-coding scheme. As noted above, this led Davis (1999) to introduce a special means for dealing with repeated letters in his SOLAR model. An additional representational layer, called a latch-field, is introduced to record letter repetitions, such that on presentation of the word BANANA, only a single letter A exists at the item level, but the different occurrences of letter A (A1, A2, and A3), are represented in the latch-field. This means that repeated letters are handled just like unrepeated letters, and should not affect processing of a stimulus. In models using ‘open bigram’ coding schemes (Grainger & van Heuven, 2003; Whitney, 2001), letter repetition implies repetition at the bigram level. Thus words containing a repeated letter will activate fewer bigrams than words without a letter repetition. For example, the word BALANCE has 21 bigram units: BA, BL, BA, BN, BC, BE, AL, AA, AN, AC, AE, LA, LN, LC, LE, AN, AC, AE, NC, NE, CE. Four of these bigrams are presented twice (the repetitions are in italics), which means that there are only 17 unique bigram codes. Thus, for a fixed word length in letters (and fixed viewing conditions), words with a repeated letter should be harder to recognise than words with no repeated letters.

Most critical for the present study, the open-bigram scheme also predicts that creating a nonword prime for the target BALANCE by omitting the second occurrence of the repeated letter (e.g., balnce), would produce significantly more priming than a nonword prime such as balace, which is created by omitting a unique letter of the target word. According to the open-bigram coding scheme, the following bigrams would be generated for a prime like balnce: BA, BL, BN, BC, BE, AL, AN, AC, AE, LN, LC, LE, NC, NE, CE. Fifteen of the seventeen unique bigrams of BALANCE are present. On the other hand, in a prime like balace there are three repeated bigrams, so in comparison with the prime balance, it has three unique bigrams less, and hence should produce less priming. Given our prior work on orthographic priming, both of these conditions are expected to produce significant priming effects relative to an unrelated condition, where no letters are shared between prime and target (Granier & Grainger, 2004).

1 In this example, removing a vowel or a consonant affects the pronounceability of the resulting nonword prime. The possible consequences of this were examined in post-hoc analyses to be discussed following Experiment 1.
EXPERIMENT 1

Experiment 1 presents a relative-position priming manipulation (primes are formed by removing one of the target’s letters) that examines the role of repeated letters in orthographic processing. Summarising the predictions for Experiment 1, the open-bigram scheme (Grainger & van Heuven, 2003; Whitney, 2001) predicts that primes formed by removing one of the repeated letters of a target word should be more effective than primes formed by removing a non-repeated letter. Furthermore, targets containing a repeated letter should be harder to identify than words without any repeated letters. On the other hand, the special scheme implemented in the SOLAR model in order to handle repeated letters (Davis, 1999) leads the model to predict that stimuli with repeated letters will be processed with approximately the same ease as stimuli with non-repeated letters. Experiment 1 puts these two alternatives to the test.

Method

Participants. Forty-four psychology students at the University of Provence participated in the experiment and received course credit in exchange. In this and the following experiments, all of the participants were native speakers of French who reported having normal or corrected-to-normal vision. All participants took part in one experiment only.

Stimuli and design. Forty-five French 7-letter words were selected as critical targets in a masked priming lexical decision experiment (Appendix 1). Their mean printed frequency was 41 per million, and ranged from 10 to 290 (New, Pallier, Ferrand, & Matos, 2001). All of these critical target words contained one letter that was repeated just once (e.g., BALANCE but not CASCADE, nor INITIAL). Care was taken so that the repeated letter did not appear on the first, nor the last position of the word (e.g., BALANCE but not AISANCE, or SILENCE, or ENFANCE). Furthermore, there was at least one intervening letter between the first and the second appearance of the repeated letter (e.g., BALANCE but not COLLINE). These constraints were used because outer letters and adjacent repeated letters (i.e., geminates) could possibly act as special cases. Plurals, feminine forms, and conjugated verbs were excluded. For all of these targets, three different types of 6-letter nonword primes were constructed (see Table 1, for an overview): (1) a related prime which was formed by omitting the second appearance of the repeated letter (omitted repeat condition, e.g., balnce as a prime for BALANCE), (2) a related prime in which the letter before or after the repeated letter was omitted (omitted unique condition, e.g., balace-BALANCE), and (3) an unrelated prime which had no letters in common with the target and had the same
CV-structure as one of the two related primes (unrelated condition, e.g., \textit{fodiru-BALANCE}). The three types of prime were all closely matched on number of orthographic neighbours. The measure used was Coltheart’s N, defined as the number of words differing by a single letter from the stimulus, preserving letter positions (e.g., worse, and house are both orthographic neighbours of horse; Coltheart, Davelaar, Jonasson, & Besner, 1977). Additionally, 45 control target words (also French 7-letter words with a mean printed frequency of 36 per million; range: 10–127) were selected. These control words did not contain a repeated letter, had

\begin{table}
\centering
\begin{tabular}{llllll}
\hline
\textit{Target type} & \textit{Freq} & \textit{N (target)} & \textit{Prime type} & \textit{N (prime)} \\
\hline
Experiment 1 & & & & \\
Repeat (BALANCE) & 40.6 & 1.1 & Omitted repeat (balance) & .33 \\
& & & Omitted unique (balace) & .40 \\
& & & Unrelated (fodiru) & .36 \\
Control (MIRACLE) & 36.0 & 1.2 & Omitted repeat* (miracle) & .42 \\
& & & Omitted unique (mirale) & .40 \\
& & & Unrelated (bentho) & .36 \\
Experiment 3 & & & & \\
5 letters (DROIT) & 84.5 & 3.34 & TL-initial (rdoit) & .03 \\
& & & TL-inner (dorit) & .03 \\
& & & TL-final (droti) & .03 \\
& & & Unrelated (cegnu) & .05 \\
7 letters (SERVICE) & 79.5 & 1.2 & TL-initial (service) & .03 \\
& & & TL-inner (sevrice) & .02 \\
& & & TL-final (serviec) & .05 \\
& & & Unrelated (notould) & .07 \\
Experiment 4 & & & & \\
5 letters (DROIT) & 84.5 & 3.34 & OC-initial (sfoit) & .05 \\
& & & OC-inner (dafit) & .05 \\
& & & OC-final (dronu) & .03 \\
& & & Unrelated (cegnu) & .05 \\
7 letters (SERVICE) & 79.5 & 1.2 & OC-initial (atrvice) & .03 \\
& & & OC-inner (sedlice) & .02 \\
& & & OC-final (serviom) & .03 \\
& & & Unrelated (notould) & .07 \\
\hline
\end{tabular}
\caption{Matched variables and examples of stimuli (in parentheses) for the different conditions tested in Experiments 1, 3, and 4}
\end{table}

* Labelled as “Omitted repeat” to match the corresponding experimental condition.
Freq: Mean printed frequency per million.

CV-structure as one of the two related primes (unrelated condition, e.g., \textit{fodiru-BALANCE}). The three types of prime were all closely matched on number of orthographic neighbours. The measure used was Coltheart’s N, defined as the number of words differing by a single letter from the stimulus, preserving letter positions (e.g., worse, and house are both orthographic neighbours of horse; Coltheart, Davelaar, Jonasson, & Besner, 1977). Additionally, 45 control target words (also French 7-letter words with a mean printed frequency of 36 per million; range: 10–127) were selected. These control words did not contain a repeated letter, had

\footnote{As indicated in Appendix 1, by error two unrelated primes did not have the same CV-structure as one of the corresponding related primes. Excluding these two items did not affect any of the results to be presented here.}
the same CV-structure as their corresponding critical target and were also matched overall on frequency and number of orthographic neighbours with the critical words. Three different prime types were constructed in the same way as for the critical target words. However, because there was no repeated letter in these control words, we omitted the letter in the same position as the omitted letter in the corresponding critical target, for all prime types respectively. This allowed us to control for any possible effect of the position of the letter that was removed to form the prime stimulus. Thus the experiment involved a $2 \times 3$ design for the participants analyses. All of these were within-participant factors. Prime-target pairing was counterbalanced using a Latin-square design. Each participant saw all targets once only in one of the three prime conditions for the two types of target, and target words were tested in all prime conditions across different participants. In the item analyses Type of target was treated as a between-items factor and Prime type was a within-items factor. In addition to the selection of ninety target words, ninety 7-letter nonwords were constructed as filler items (since the task was lexical decision). Half of these nonwords had a repeated letter, whereas the other half did not (Appendix 2). These two subgroups were matched on number of orthographic neighbours and CV-structure. Primes were constructed for the nonword targets following the same procedure as for the words. In fact, the design for nonword targets mirrored that of the words.

Procedure. Each trial consisted of a sequence of four visual events. The first was a row of nine hash marks (##########), which served as a forward mask, and was presented for 500 ms together with two vertical lines positioned above and below the centre of the mask and serving as a fixation mark. Second, the prime was displayed on the screen for 53 ms and was followed immediately by a backward mask for 13 ms. Finally, the target was presented for a maximum duration of 4000 ms, or until participant’s response. Each stimulus appeared in the centre of the screen. The intertrial interval was 523 ms. Stimulus presentation and response collection were controlled by DMDX and TimeDX software Version 3.02 (Forster & Forster, 2003). All stimuli were presented on a standard 15” VGA colour monitor (with a 13.32 ms refresh rate) in fixed-width ‘Courier New’ font, as white characters on a black background. Primes appeared in lower case (font size 12), whereas targets were presented in upper case (font size 16). For the masks, the same font size as for the primes was used. The presentation of all trials was randomised with a different order for each participant. Participants were asked to focus on the centre of the row of hash marks (indicated by the two vertical lines) and to decide as quickly and accurately as possible if the stimulus in upper case was a French word.
or not. The two possible response buttons were the right control key (for a ‘Yes’ response) and the left control key (for a ‘No’ response) of a standard PC keyboard. The assignment of responses was reversed for left-handed participants. None of the participants was informed about the presence of a prime.

Results

Mean response times and percentage error are presented in Table 2. Only correct responses were analysed after removing outliers (RTs greater than 250 ms or less than 1500 ms). This procedure affected less than 1% of all data for correct responses. ANOVAs were carried out with participants \( (F_1) \) and items \( (F_2) \) as random variables. In the participants analyses List was included as a between-participants factor, and figured as a between-item factor in the item analyses. For all experiments reported in the present study, this same procedure of analysis was used.

<table>
<thead>
<tr>
<th>Type of target</th>
<th>Type of prime</th>
<th>Mean RT (ms)</th>
<th>Errors</th>
<th>Mean RT (ms)</th>
<th>Errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Words</td>
<td>Omitted repeat</td>
<td>565***</td>
<td>3%</td>
<td>560***</td>
<td>2%</td>
</tr>
<tr>
<td></td>
<td>Omitted unique</td>
<td>572***</td>
<td>3%</td>
<td>561***</td>
<td>2%</td>
</tr>
<tr>
<td></td>
<td>Unrelated</td>
<td>607</td>
<td>6%</td>
<td>597</td>
<td>3%</td>
</tr>
<tr>
<td>Nonwords</td>
<td>Omitted repeat</td>
<td>695</td>
<td>5%</td>
<td>677***</td>
<td>5%</td>
</tr>
<tr>
<td></td>
<td>Omitted unique</td>
<td>686</td>
<td>6%</td>
<td>670</td>
<td>4%</td>
</tr>
<tr>
<td></td>
<td>Unrelated</td>
<td>691</td>
<td>6%</td>
<td>672</td>
<td>4%</td>
</tr>
</tbody>
</table>

** *** \( p < .001 \): significant differences relative to the unrelated condition.

Further item analyses were performed including log word frequency as a covariate. This did not change the significance level of any of the results reported here.

### Word analyses

An ANOVA on mean RTs showed that targets containing a repeated letter took longer to respond to than targets without a repeated letter, \( F_1(1, 41) = 7.38, p < .05 \), although this effect was not significant in the items analysis, \( F_2(1, 84) = 0.97 \). There was a main effect of Prime type, \( F_1(1, 82) = 46.29, p < .001 \), \( F_2(2, 168) = 49.74, p < .001 \). The interaction between Target type and Prime type was not significant. Planned comparisons between the different prime conditions indicated that the related prime condition produced significantly faster RTs than the
unrelated prime condition: $F_1(1, 41) = 59.64, p < .001, F_2(1, 84) = 67.32, p < .001$, for the omitted repeat condition, and $F_1(1, 41) = 60.47, p < .001, F_2(1, 84) = 31.94, p < .001$, for the omitted unique condition. A planned comparison for the repeat targets only, showed that the difference between the two related prime conditions (i.e., omitted repeat vs. omitted unique) was not significant. An ANOVA conducted on error percentages to word targets yielded a significant main effect of Target type, $F_1(1, 41) = 10.16, p < .01, F_2(1, 84) = 4.79, p < .05$. Accuracy was lower for words containing a repeated letter.

Nonword analyses. An ANOVA conducted with RT as dependent variable, revealed a main effect of Target type, $F_1(1, 41) = 18.45, p < .01$, that was not significant in the item analysis, $F_2(1, 84) = 2.07$. In the accuracy analysis, the main effect of Target type was also significant in the participants analysis, $F_1(1, 41) = 6.62, p < .05$, but not in the item analysis, $F_2(1, 84) = 1.44$. Nonword targets without a repeated letter tended to generate faster RTs and less errors than nonword targets containing a repeated letter.

Discussion

The results of Experiment 1 provide mixed support for both the SOLAR model (Davis, 1999) and open-bigram accounts of letter position coding (Grainger & van Heuven, 2003; Whitney, 2001). The fact that primes formed by removing a repeated letter in the target word were not more effective than other orthographically related primes contradicts the predictions of the open-bigram scheme. This absence of an influence of letter repetition on orthographic priming was further explored with post-hoc analyses examining whether the CV-status of the removed letter affected priming. Priming effects were compared for primes formed by removing a consonant vs. primes formed by removing a vowel. Separate analyses were performed for the omitted repeat and omitted unique priming conditions. These analyses showed significant priming effects for omitted repeat, $F(1, 82) = 17.01, p < .01$, and omitted unique primes, $F(1, 82) = 47.25, p < .001$, that did not interact with the CV-status of the letter that was removed to form the related prime, $F(1, 82) = 1.22$ and $F < 1$ respectively. There was a 32 ms priming effect for primes formed by removing a consonant and a 42 ms effect for primes formed by removing a vowel. Furthermore, a direct comparison of the two types of prime revealed no significant difference. The CV-status of the letter that was removed to form a related prime in Experiment 1, did not affect the amount of priming that was obtained.

The open-bigram model correctly predicted the main effect of target type observed in Experiment 1: targets containing a repeated letter were
harder to respond to (more errors and slower RTs) than targets without a repeated letter. This repeated-letter effect was observed for both word and nonword stimuli. This is, to our knowledge, the first report of an influence of repeated letters on printed word perception. Nevertheless, the fact that the effect in RTs to word targets failed to reach significance in the item analyses suggests that further research is necessary to consolidate this potentially critical finding.

The priming effects observed in Experiment 1, or rather the lack of an influence of the repeated-letter manipulation in prime stimuli, contradicts the open-bigram model. According to this model, primes generated by removing one of a repeated letter pair in a target word share more bigrams with the target word than primes generated by removing a non-repeated letter. This priming condition should therefore have generated stronger priming effects. The fact that this did not occur is more in line with the predictions of the SOLAR model (Davis, 1999). However, one means of saving the open-bigram model would be to argue that the masked priming paradigm is not sensitive enough to detect the rather subtle manipulation of prime type in Experiment 1. If nonword primes formed by removing a repeated letter from a given word provide more activation input to their corresponding base-word than nonwords formed by removing a non-repeated letter, then these nonwords should be harder to reject as targets in an unprimed lexical decision task. This was tested in Experiment 2.

**EXPERIMENT 2**

Experiment 2 is an unprimed lexical decision experiment where the critical targets are the nonword primes from Experiment 1.

**Method**

*Participants.* Forty psychology students at the University of Provence participated in this experiment for course credit.

*Stimuli and design.* Stimuli were the 270 six-letter nonwords that had served as primes for word targets in Experiment 1, and 90 six-letter word targets. The latter were used as filler items for the lexical decision task (here the focus was on performance to nonword targets), and had a mean printed frequency of 26 per million (New et al., 2001). There was no experimental manipulation of the word stimuli. Critical targets were therefore 135 nonword targets derived from words with repeated letters (45 repeat word targets from Experiment 1 × 3 prime types) and 135 control nonword targets, based on words without a repeated letter. Following the counterbalancing of Experiment 1, three lists were generated, each containing 90 critical nonword targets and 90 word
targets. This gave a 2 (Type of base-word: Repeated letter vs. Control) × 3 (Target type: Omitted repeat vs. Omitted unique vs. Unrelated) design for the participants analyses. Both of these factors were manipulated within-participants. The same design was used in the item analyses, where both factors were between-items factors.

Procedure. Each trial consisted of a simple sequence of two events, as used in standard lexical decision. A fixation point (*) appeared initially in the centre of the screen, and was replaced by the target after 500 ms. The target itself was presented for a maximum duration of 4000 ms, or until participant’s response. Targets appeared in lower case, fixed-width ‘Courier New’ font (font size 12). In general, the same procedure as in Experiment 1 was used for stimulus presentation and data collection (except for the differences mentioned above).

Results

Mean response times and percentage of errors are presented in Table 3. Outliers were removed as in Experiment 1. An ANOVA conducted on responses to nonword targets with RT as dependent variable, revealed no main effect of Type of base-word, but a significant main effect of Target type, $F_1(2, 74) = 74.48, p < .001, F_2(2, 252) = 39.10, p < .001$. The interaction was not significant. Planned comparisons between the different target conditions showed that the main effect of Target type was due to significantly slower RTs for the two categories of nonwords generated by removing a letter from a real word (omitted repeat and omitted unique) as opposed to the unrelated condition, respectively $F_1(1, 37) = 51.47, p < .001, F_2(1, 252) = 30.80, p < .001$, and $F_1(1, 37) = 130.71, p < .001, F_2(1, 252) = 76.34, p < .001$. An ANOVA on percentages of error also revealed a significant main effect of Target type, $F_1(2, 74) = 39.16, p < .001, F_2(2, 252) = 17.30, p < .001$, no effect of Type of base-word, and no interaction.

<table>
<thead>
<tr>
<th>Type of target</th>
<th>Repeat Mean RT</th>
<th>Repeat Errors</th>
<th>Control Mean RT</th>
<th>Control Errors</th>
</tr>
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<tbody>
<tr>
<td>Omitted repeat</td>
<td>714***</td>
<td>11%***</td>
<td>694***</td>
<td>10%***</td>
</tr>
<tr>
<td>Omitted unique</td>
<td>736***</td>
<td>9%***</td>
<td>736***</td>
<td>11%***</td>
</tr>
<tr>
<td>Unrelated</td>
<td>659</td>
<td>2%</td>
<td>646</td>
<td>1%</td>
</tr>
</tbody>
</table>

*** $p < .001$: significant differences relative to the unrelated condition.
Planned comparisons between the different target conditions indicated that the error percentages were significantly higher for the two categories of nonwords derived by removing a letter from a real word as opposed to unrelated nonwords, respectively $F_1(1, 37) = 57.34, p < .001$, $F_2(1, 252) = 27.83, p < .001$ for the omitted repeat nonwords, and $F_1(1, 37) = 68.88, p < .001$, $F_2(1, 252) = 23.91, p < .001$, for the omitted unique nonwords. No other significant differences were found.

**Discussion**

The results of Experiment 2 provide a further demonstration of how similarity with a real word can influence responses to nonword targets in the lexical decision task. Nonwords formed by removing a letter from a real word were harder to reject (more errors and slower RTs) than nonwords that were matched in terms of number of orthographic neighbours (Coltheart et al., 1977). However, contrary to the predictions of the open-bigram model, nonwords formed by removing a repeated letter (e.g., BALNCE from BALANCE) were not harder to respond to than nonwords formed by removing a non-repeated letter (e.g., BALACE from BALANCE, or MIRCLE from MIRACLE). This result is in line with models of orthographic processing that have a specific mechanism for dealing with letter repetitions, such as the SOLAR model (Davis, 1999).

However, there is one very simple, and theoretically justified modification of the open-bigram model that allows it to capture the general pattern of results obtained in Experiments 1 and 2. This involves imposing a limit on the number of letters that can be inserted in between the two letters that form the open-bigram. This amounts to imposing a limit on the degree of “coarseness” of the coding scheme. We are not the first to suggest such a constraint on open-bigram coding. Humphreys et al. (1990), when discussing Mozer’s BLIRNET model in the light of their own data, suggested that the model could be refined such that “... the degree to which input activates cluster units decreases as the distance between letters increases (p. 550).” And Whitney (2001) states that “The activation of a bigram node depends on the activation of the letter nodes representing its constituent letters (increasing activation with increasing input levels) and the time separation between the firing of those letter nodes (decreasing activation with increasing separation) (p. 227).”

Although we completely adhere to a graded activation approach as suggested by Humphreys et al. (1990) and Whitney (2001), for simplicity we will assume an arbitrary limit of two intervening letters beyond which no bigrams are formed. This allows us to generate albeit approximate predictions from the revised model, without having to implement graded activation input from peripheral letter representations. Thus the open-
bigrams for the word BALANCE are now limited to: BA, BL, (BA), AL, AA, AN, LA, LN, LC, AN, AC, AE, NC, NE, CE. This scheme still predicts that words with repeated letters should be handicapped relative to words without repeated letters. More important, it now accounts for the lack of an effect of the nonword manipulation in Experiment 1 (as primes) and Experiment 2 (as targets). Both types of prime now generate an equivalent number of overlapping bigrams with the target (10 bigrams for the nonword BALNCE: BA, BL, (BN), AL, AN, AC, LN, LC, (LE), NC, NE, CE. Ten bigrams for the nonword BALACE: BA, BL, AL, AA, AC, LA, LC, (LE), AC, AE, CE).

This constrained version of the open-bigram model was directly motivated by the results of Experiments 1 and 2 of the present study. However, it is important to note that this critical modification of the open-bigram model has since been successfully applied to a large set of relative-position priming results described in Grainger and van Heuven (2003) and Granier and Grainger (2004). The new version of the model provides a complete account of these data, that the old version could only partly account for (we will return to this point in the general discussion). One interesting consequence of the new coding scheme is that stimulus length now influences the extent to which open-bigrams cover all possible ordered letter combinations that can be generated by a given stimulus. As stimulus length increases, the proportion of bigrams that are computed in the new scheme will diminish relative to the complete set of unconstrained bigrams. This leads to length-dependent predictions concerning effects of transposed letters, to be examined in Experiment 3.

EXPERIMENT 3

Experiment 3 examines the influence of transposed letters in the masked priming paradigm. This has been the subject of a recent study published by Perea and Lupker (2003), who provide an excellent summary of research on this topic. Here we first summarise results obtained using the masked priming paradigm, before presenting the predictions of the models that are to be put to test.

Letter transposition priming

In standard masked priming with the lexical decision task and relatively long target words, Forster, Davis, Schoknecht, and Carter (1987) found that effects of transposed letter primes (e.g., salior-SAILOR) were practically the same as identity primes (e.g., sailor-SAILOR). With shorter words (Humphreys et al., 1990), or when primes do not contain all of the target’s letters (Peressotti & Grainger, 1999), then transposition priming is greatly diminished. Using their 4-field masking procedure and
perceptual identification responses to targets, Humphreys et al. (1990) found only a non-significant 3.1% increase in response accuracy for transposed letter primes (e.g., snad-SAND) compared with primes sharing two out of four letters with targets (e.g., smed-SAND). Similarly, Peressotti and Grainger (1999, Experiment 3a) observed a non-significant 5 ms advantage relative to all different primes when the inner letters were transposed in primes sharing four out of six letters with targets (e.g., bcln-BALCON).

More recent work on transposed letter priming by Perea and Lupker (2003) has provided support to the initial observation of Forster et al. (1987), and helped clarify the precise conditions in which these effects are obtained. In Perea and Lupker’s study, transposed letter primes were formed by exchanging two of the target’s inner letters (inner transposition; e.g., uhser-USHER) or by exchanging the last two letters of the target (final transposition; e.g., ushre-USHER). Effects of transposition primes were evaluated against an all-different letter prime or an orthographic control prime where the two transposed letters were replaced by letters not in the target (e.g., ufner, ushno). In 5- and 6-letter words, priming effects relative to the unrelated condition did not vary as a function of position of the transposition. However, when measured relative to orthographic control primes, Perea and Lupker (2003) report a significant effect for inner transposition primes that greatly diminishes for the final transposition condition.

Predictions for Experiment 3

Here we will briefly summarise the predictions of three models of letter position coding that provide the focus of the present study. The SOLAR model (Davis, 1999), the SERIOL model (Whitney, 2001), and the new version of the open-bigram scheme presented above, all predict effects of transposed letter primes in the masked priming paradigm. One potential difference between activation gradient accounts of letter position coding (Davis, 1999; Whitney, 2001) and parallel activation accounts (Grainger & van Heuven, 2003; Mozer, 1987) are their predictions concerning effects of positional bias in transposition priming. However, the activation gradient used to generate a spatial orthographic code does not necessarily translate into a straightforward beginning-to-end positional bias at higher-level representations. The equations used in the SOLAR model (Davis, 1999) actually lead it to predict no positional biases in transposition priming. In the SERIOL model (Whitney, 2001), the activation profile of bigram units does not decrease monotonically from beginning to end. This model does

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4 We thank Colin Davis for having pointed this out.
nevertheless predict that least priming should be obtained when an initial bigram is modified in the prime. This is because the initial bigram carries the most activation in the SERIOL model, as can be seen in the equations and the examples provided in Whitney and Berndt (1999).

The new version of the parallel open-bigram scheme makes an interesting prediction concerning variations in positional bias as a function of word length. The predictions of the new open-bigram scheme (with maximum two intervening letters) for the three types of related prime and the two word lengths tested in Experiment 3 are as follows. For 5-letter words, initial and final transposition primes share 7 out of 9 bigrams with targets, while inner transposition primes share 8 bigrams with targets. For 7-letter words, all three types of prime share 13 out of 15 bigrams with targets. Thus, the model predicts an inner letter transposition advantage (relative to initial and final transpositions) for 5-letter words, and equivalent priming effects for all three types of prime with 7-letter words. Experiment 3 tests for such positional biases by using primes formed by transposing two adjacent letters at the beginning, in the middle, or at the end of a given target word.

Method

Participants. Thirty-seven psychology students at the University of Provence participated in the experiment for course credit.

Stimuli and Design. A set of 120 items were selected to be used as word targets (Appendix 3). Sixty words of 5-letters (mean printed frequency 85 per million; range 10–452, New et al., 2001) and sixty words of 7-letters (mean printed frequency 80 per million; range 10–353) were included. Four types of prime were created for all targets (see Table 1). These primes were formed by (1) transposing the first two letters of targets (TL-initial, e.g., rdoit as prime for DROIT); (2) transposing the two middle letters of targets, i.e., the second and third position or third and fourth position for 5-letter words, and the third and fourth, or fourth and fifth position for 7-letter words (TL-inner, e.g., dorit-DROIT); (3) transposing the two final letters of targets (TL-final, e.g., droti-DROIT); or were (4) unrelated to targets (e.g., cegnu-DROIT). All these prime types were closely matched on number of orthographic neighbours (Coltheart et al., 1977), and all were nonwords. Thus a 2 (Stimulus length: 5 letters vs. 7 letters) × 4 (Prime type: TL-begin vs. TL-inner vs. TL-final vs. unrelated) repeated measures design was used in the participants analyses. For the item analyses, the same design was used but Stimulus length was treated as a between-items factor. Additionally, 120 nonwords (sixty 5-letter and sixty 7-letter nonwords) were created as filler items for the lexical decision
task. The manipulation of the nonword targets was the same as for the word targets. A Latin-square was used to create four completely counterbalanced presentation lists, with each list containing all 240 targets. The primes in the four lists were again matched on number of orthographic neighbours. All participants were exposed to only one presentation list, and given the counterbalancing, each participant was tested in all experimental conditions with a given target presented only once.

Procedure. The same masked priming procedure as Experiment 1 was used here, except that different font sizes were used. Primes were presented in lowercase (font size 16), and targets in uppercase (font size 12). The forward mask had the same font size as the primes. The different size and case used for prime and target stimuli minimizes visual overlap in the related prime condition when primes and targets have the same length in letters.

Results

Mean response times and percentage error are presented in Table 4. Outliers were removed as in the previous analyses. However, a preliminary analysis showed mean error rates higher than 40% on two 5-letter words, two 7-letter words, and one seven-letter nonword. These items were excluded from further analysis.

Word analyses. An ANOVA on mean RTs revealed significant main effects of Stimulus length and Prime type, respectively $F(1, 33) = 679.42, p < .001$, $F(2, 109) = 3.76, p < .06$, and $F(1, 99) = 9.78, p < .001$, $F(3, 327) = 6.92, p < .001$. Their interaction was marginally significant in the participants analysis, $F(1, 99) = 2.61, p < .06$, and significant in the item analysis $F(3, 327) = 2.97, p < .05$. This trend to an interaction reflects the greater magnitude of priming effects with 7-letter words compared with 5-letter words. Planned comparisons for the 5-letter words indicated that TL-inner primes produced significantly shorter RTs compared with the unrelated prime condition, $F(1, 33) = 8.90, p < .01$, $F(2, 109) = 4.36, p < .05$. The TL-initial and TL-final prime conditions did not differ significantly from the unrelated prime condition with 5-letter words. For 7-letter words, planned comparisons showed that all related (TL) prime conditions were faster than the unrelated condition: TL-initial

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5 The reason for this change is that in pilot experimentation with transposed-letter primes we had found stronger priming effects with this particular combination of prime and target sizes.
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primes, $F_1(1, 33) = 10.75, p < .01, F_2(1, 109) = 20.40, p < .001$, TL-inner primes, $F_1(1, 33) = 14.92, p < .001, F_2(1, 109) = 15.13, p < .001$, and TL-final primes, $F_1(1, 33) = 21.83, p < .001, F_2(1, 109) = 14.86, p < .001$.

An ANOVA with percentage of error as dependent variable revealed a significant main effect of Stimulus length $F_1(1, 33) = 47.50, p < .001, F_2(1, 109) = 15.52, p < .001$. Five-letters words produced more errors than seven-letter words. The main effect of Prime type was not significant. The interaction between Stimulus length and Prime type was significant in the participant analysis, $F_1(3, 99) = 2.98, p < .05$, but failed to reach significance in the item analysis, $F_2(3, 327) = 1.85, p < .07$.

**Nonword analyses.** An ANOVA on mean RTs revealed a significant interaction between Stimulus length and Prime type, $F_1(3, 99) = 3.63, p < .05, F_2(3, 333) = 2.83, p < .05$. No main effects were significant. Planned comparisons for the 5-letter nonwords showed that TL-inner primes produced significantly shorter RTs compared to the unrelated prime condition, $F_1(1, 33) = 8.90, p < .01, F_2(1, 111) = 9.86, p < .01$. None of the other prime conditions differed significantly from the unrelated condition in either 5-letter or 7-letter nonwords. An ANOVA conducted on the mean percentage of errors revealed a main effect of Stimulus length, $F_1(1, 33) = 29.30, p < .001, F_2(1, 111) = 13.44, p < .001$. Five-letter nonwords produced significantly more errors than 7-letter nonwords. There was no effect of Prime type, and no interaction.

<table>
<thead>
<tr>
<th>Prime type</th>
<th>5 Letters</th>
<th>7 Letters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean RT</td>
<td>Errors</td>
</tr>
<tr>
<td>Words</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Initial</td>
<td>616</td>
<td>6%</td>
</tr>
<tr>
<td>2. Inner</td>
<td>597**</td>
<td>8%</td>
</tr>
<tr>
<td>3. Final</td>
<td>613</td>
<td>9%</td>
</tr>
<tr>
<td>4. Unrelated</td>
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<td>7%</td>
</tr>
<tr>
<td>Nonwords</td>
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<tr>
<td>1. Initial</td>
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<td>8%</td>
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<tr>
<td>2. Inner</td>
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<td>3. Final</td>
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<td>7%</td>
</tr>
<tr>
<td>4. Unrelated</td>
<td>721</td>
<td>7%</td>
</tr>
</tbody>
</table>

* $p < .05$; ** $p < .01$; *** $p < .001$; significant differences relative to the unrelated condition.
Discussion

Consistent with the predictions of the new open-bigram scheme for letter position coding, 7-letter words showed equivalent effects from primes generated by transposing the first two letters (TL-initial), the last two letters (TL-final), and an inner letter pair (TL-inner). Again consistent with the predictions of the new coding scheme, 5-letter words showed significant priming only from TL-inner primes. The fact that a positional bias was observed with 5-letter words is not consistent with the predictions of the SOLAR model (Davis, 1999). Furthermore, there was no evidence for reduced priming with initial letter transpositions compared with final letter transpositions, as predicted by the SERIOL model (Whitney, 2001).

The results for 5-letter words replicate and extend those reported in Perea and Lupker (2003). However, Perea and Lupker found a similar pattern of priming effects for 6-letter words, while our results for 7-letter words did not show the expected inner letter transposition advantage relative to TL-final primes (Perea & Lupker did not test for TL-initial primes). It is interesting to note that in Perea and Lupker’s study, TL-inner and TL-final primes generated very similar RTs (529 ms vs. 534 ms) which is perfectly consistent with the results of the 7-letter words in our Experiment 3. The difference in priming effects in their study only arose in a comparison with orthographic control primes. The orthographic control involved substituting the two critical letters of a given TL prime with two unrelated letters (e.g., TRANI (TL) and TRAPO (control) for the target TRAIN). In Perea and Lupker’s study, orthographic control primes involving a substitution of inner letters produced longer RTs than orthographic controls involving final letter substitution (hence the stronger priming effect for TL-inner primes). Experiment 4 examines priming effects for 2-letter substitution primes (following Perea & Lupker, 2003) matched to the TL primes tested in Experiment 3. The new open-bigram scheme predicts no effects of 2-letter substitution primes relative to unrelated primes, given the very low degree of overlap with targets (3 out of 9 bigrams for 5-letter words, and 9 out of 15 for 7-letter words).

EXPERIMENT 4

Method

Participants. Thirty-nine psychology students at the University of Provence participated in the experiment for course credits.

Stimuli and design. The target stimuli of Experiment 3 were used again. Three new prime types, which served as orthographic controls for the transposed letter primes of Experiment 3, were created for the purpose
of the present experiment (Appendix 3). The orthographic controls (OC) were identical to the TL primes except that the transposed letters were now replaced by two other letters. The three types were: (1) OC-initial, e.g., *sfoit* (instead of *rdoit*) as prime for DROIT; (2) OC-inner, e.g., *dafit-DROIT* (instead of *dorit-DROIT*); and (3) OC-final, e.g., *dronu-DROIT* (instead of *droti-DROIT*). The unrelated prime condition (e.g., cegnu-DROIT) was the same as for Experiment 3 (see Table 1, for an overview). All these prime types were closely matched on number of orthographic neighbours (Coltheart et al., 1977). The same procedure for construction of orthographic control primes was used for the nonword targets. The primes in the four lists were again matched on number of orthographic neighbours. The experiment involved a 2 (Stimulus length; 5 letters vs. 7 letters) × 4 (Prime type; OC-begin vs. OC-inner vs. OC-final vs. unrelated) repeated-measures design in the participants analyses, with counterbalanced lists as in Experiment 3.

**Procedure.** The procedure was the same as for Experiment 3.

**Results**

Mean response times and percentage errors are presented in Table 5. Outliers were removed as in the previous analyses. The same items that were removed from the analyses in Experiment 3, were once again the items that generated the highest error rates. They were excluded from further analysis.

<table>
<thead>
<tr>
<th>Prime type</th>
<th>5 Letters</th>
<th>7 Letters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean RT</td>
<td>Errors</td>
</tr>
<tr>
<td><strong>Words</strong></td>
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<tr>
<td>1. Initial</td>
<td>622</td>
<td>5%</td>
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<tr>
<td>2. Inner</td>
<td>626</td>
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<td>3. Final</td>
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<td>4. Unrelated</td>
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<tr>
<td>4. Unrelated</td>
<td>740</td>
<td>8%</td>
</tr>
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</table>

*p* < .05; significant differences relative to the unrelated condition.
**Word analyses.** An ANOVA on mean RTs revealed a significant main effect of Stimulus length, $F_1(1, 35) = 24.11, p < .001$, $F_2(1, 108) = 6.48, p < .05$. Seven-letter words produced significantly faster RTs than five-letter words. Neither the main effect of Prime type, nor the interaction between Stimulus length and Prime type were significant. An ANOVA on percentage of error revealed a significant main effect of Stimulus length, $F_1(1, 35) = 30.21, p < .001$, $F_2(1, 108) = 8.43, p < .01$. Five-letter words produced significantly more errors than seven-letter words. No other significant effects were found. The only planned comparison (against the unrelated prime condition) to reach significance was the effect of OC-final primes for 7-letter targets, $F_1(1, 35) = 6.48, p < .05$, $F_2(1, 108) = 5.16, p < .05$.

**Nonword analyses.** The only main effect to reach significance in the latency and accuracy analyses for nonwords, was the effect of Stimulus length in the accuracy analysis, $F_1(1, 35) = 34.78, p < .001$, $F_2(1, 111) = 14.30, p < .001$. Five-letters nonwords produced significantly more errors than 7-letter nonwords.

**Discussion**

The results of Experiment 4 show that the level of orthographic overlap across prime and target with 2-letter substitution primes is not great enough to significantly affect performance relative to the unrelated prime condition. There is, however, some evidence for a positional bias in the results for 7-letter words. The substitution primes involving the two last letters of target words produced a 16 ms facilitation relative to the unrelated prime condition. Although somewhat smaller than the 31 ms effect reported by Perea and Lupker (2003), it is in the same direction. This result lends some support to Perea and Lupker’s argument that, when compared with orthographic control primes (with two adjacent letters substituted), then transposition priming effects may be stronger when the transposition involves two inner letters compared with when it involves the two last letters. Most important, however, is the fact that there was no difference between the initial letter and inner letter substitution conditions in Experiment 4. This implies that the results for initial letter and inner letter transposition primes in Experiment 3 are due to the transposition manipulation and not to the other letters shared by prime and target. This therefore consolidates the critical pattern showing an inner letter transposition advantage for 5-letter words that disappears with 7-letter targets. This pattern was predicted by the new version of the open-bigram coding scheme involving a constraint on the number of possible intervening letters.
GENERAL DISCUSSION

The results of the present study were designed to test three recent models of letter position coding that appeared particularly promising in the light of recent data obtained with the masked priming paradigm. These are Davis’ (1999) SOLAR model, Whitney’s (2001) SERIOL model, and the open-bigram model developed conjointly by Grainger and van Heuven (2003) and the present authors. These particular models can account for relative-position priming effects, where prime stimuli sharing letters in the same relative position as target words (e.g., 13457, for a 7-letter word) facilitate target processing to the same extent as primes sharing letters in the same absolute position as targets (Granier & Grainger, 2004; Humphreys et al., 1990; Pesciarelli et al., 2001; Peressotti & Grainger, 1999). These three models were put to further test in the present study by manipulating the presence or not of repeated letters in prime and target stimuli, and by testing stimuli with transposed letters in the masked priming paradigm.

Repeated letters

In Experiments 1 and 2 of the present study, a repeated letter manipulation was used, such that target words containing a repeated letter (e.g., BALANCE) were primed by stimuli formed either by removing one of the repeated letters (balnce), or by removing one of the non-repeated letters (balace). Priming effects were compared with those obtained with target words without repeated letters. In line with the predictions of both the SERIOL model (Whitney, 2001) and Grainger and van Heuven’s (2003) open-bigram model, and contrary to the predictions of the SOLAR model (Davis, 1999), words with repeated letters were harder to process than words without repeated letters. However, in line with the SOLAR model and contrary to the other two models, the status of repeated letters had no influence whatsoever on priming effects. Experiment 2 tested the nonword primes of Experiment 1 as targets in an unprimed lexical decision task. Nonwords created by removing a letter from a real word were harder to reject than control nonwords. However, once again the status of repeated letters had no influence on the processing of such stimuli.

Open-bigram coding schemes predicted an influence of repeated letters at all levels of performance (as a main effect on target processing, and as a modulator of priming effects). Letter repetition leads to the generation of a smaller number of bigrams, hence lower-levels of activation input to lexical representations (for a fixed level of activation in more peripheral letter representations), and lower levels of orthographic overlap across prime and target stimuli in a priming situation. However, the prediction
that maintaining repeated letters in a prime stimulus (e.g., balace, for the
target BALANCE) should lead to less priming than when one of the
repeated letters is removed (e.g., balnce), only holds when open-bigrams
are formed across all letters in the stimulus with an unlimited number
of intervening letters. When the number of intervening letters is limited
to two, then this prediction no longer holds (see discussion of
Experiment 2).

This modified open-bigram scheme forms the basis of a model that has
been conjointly developed and tested by Grainger and van Heuven (2003).
A further motivation for the new coding scheme was found in some
relative-position priming experiments. These experiments examined the
effects of 5-letter relative-position primes on the processing of 7-letter
target words, with primes formed by the first and last letter of target words
plus varying combinations of three inner letters. In one critical experiment,
three conditions produced significant facilitation relative to an all-different
letter prime (ddddd). These were prime conditions 12457, 13457, and
13467. Three conditions failed to generate significant facilitation relative to
unrelated primes. These were prime conditions 12367, 12467, and 12567.
The original open-bigram scheme could not account for these differences.
The new scheme does. Prime conditions 12457, 13457, and 13467, share
seven out of nine bigrams with their corresponding targets (readers are
invited to check this for themselves). On the other hand, prime conditions
12367, 12467, and 12567, share only five or six out of the target’s nine
bigrams. If the minimum orthographic overlap required to observe
significant priming is seven out of nine, then the new coding scheme
captures this complex pattern of priming effects.

Transposed letters

A further significant test of the new open-bigram coding scheme was
provided in Experiment 3, where letter transposition was manipulated
across prime and target. Letter transposition effects provide a strong test
of models of letter position coding. The three models that served as the
theoretical focus of the present study can account for priming effects
obtained when primes are created by transposing two of the target word’s
letters (Forster et al., 1987; Perea & Lupker, 2003). All slot-based coding
schemes fail on this test, except for those using staggered presentation
techniques (Shillcock & Monaghan, 2001). Standard bigram or trigram
schemes (e.g., Seidenberg & McClelland, 1987) also fail, since letter
transposition disrupts the number of correct n-grams in the prime stimulus
(for example, the prime BLCAK retains only one trigram from the target
BLACK: #BL, and only two bigrams: #B, and BL).
The SOLAR model (Davis, 1999), the SERIOL model (Whitney, 2001), and the open-bigram model (Grainger & van Heuven, 2003), can all account for priming effects obtained with letter transpositions. However, only the new version of the open-bigram model, motivated by the results of Experiments 1 and 2 of the present study plus the relative-position priming data of Granier and Grainger (2004), could predict the specific pattern of results obtained in Experiment 3. In this experiment, transposed letter primes only facilitated performance to 5-letter targets when the transposition involved inner letters. Initial and final-letter transposition did not facilitate target processing relative to unrelated primes in 5-letter target words. With 7-letter target words, priming effects were obtained independently of the position of transposition (initial, inner, final). SERIOL predicted a disadvantage for initial-letter transpositions that was not observed, while SOLAR predicted no positional biases in transposition priming. As noted by Perea and Lupker (2003), however, in one version of the SOLAR model, an advantage has been given to final letter activation such that inner-letter transpositions could actually generate more priming than final letter transpositions. Nevertheless, this version of the SOLAR model would still have difficulty in accommodating the fact that the inner-letter transposition advantage was length dependent, only occurring for 5-letter words.

Further evidence against any beginning-to-end bias in orthographic processing was presented in the introduction to the present study.6 We noted some recent work on relative-position priming that provides converging evidence against any form of beginning-to-end positional bias in orthographic priming. Granier and Grainger (2004) compared relative-position primes formed by the first letters of targets, the last letters, or a combination of the first, last, and some inner letters. The results are most striking for 9-letter targets. Prime conditions 12345 and 56789 generated equivalent amounts of priming, and stronger priming than the 14569 prime condition. The new open-bigram scheme captures this pattern of priming effects, whereas this pattern was not predicted by either SERIOL or SOLAR. It should be noted, however, that positional biases can arise via other factors such as variations in letter visibility and lexical constraint (Clark & O’Regan, 1999; Grainger & Jacobs, 1993; Stevens & Grainger, 2003). Only further experimentation will allow us to separate out the effects due to a particular form of orthographic coding from the influences of other possible factors.

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6 We acknowledge the evidence in favour of serial processing during reading aloud (e.g., Rastle & Coltheart, 1999), but would argue that this is specific to the act of articulation which requires a serial output.
Conclusions

The present study provides a modest contribution to a fast developing area of research using (mostly, but not exclusively) the masked priming paradigm to investigate early orthographic processing in printed word perception. Several studies have shown that the orthographic code for printed strings of letters involves some form of relative-position information for a set of letter identities (Forster et al., 1987; Granier & Grainger, 2003; Humphreys et al., 1990; Perea & Lupker, 2003; Peressotti & Grainger, 1999; Pesciarelli et al., 2001). Adopting a relative-position code implies that the processing system has knowledge about order information of the type “B is after A and before C”, and that this will be true for the string ABC and also for the string AGBMC. The notion of “open-bigram” was introduced to capture the essence of this type of coding. The present study provides further evidence in favor of such relative-position coding of printed strings of letters, and suggests that there is a constraint on the number of possible intervening letters in open-bigram coding. Future research will provide further tests of this approach to letter position coding.

REFERENCES


## Appendix 1

Word targets and the corresponding nonword primes tested in Experiment 1

<table>
<thead>
<tr>
<th>Repeat</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target</td>
<td>Omitted</td>
</tr>
</tbody>
</table>

| PROGRÈS | progès | progrs | blumit | CHARBON | charon | charbn | plevus |
| PLACARD | placrd | placad | thonis | PRUDENT | prudnt | prudet | chabol |
| PROFOND | profnd | profod | blameg | FLAFOND | plafnd | plafod | bivret* |
| CRAVATE | cravte | cravae | spigio | FROMAGE | fromge | fromae | thulin* |
| GLOBALE | globae | globle | fristu | FRAGILE | frage | fragile | chontu |
| CHINOIS | chinos | chinis | trubal | SPECIAL | spécil | spécal | grunot |
| STATION | staion | staton | drugel | CHAIRE | chaeur | chalur | stind |
| TRAVAIL | travil | traval | snedum | PRODUIT | prodit | produt | snavel |
| SERGENT | sergnt | serget | balzuc | MECHANT | méchnt | méchat | virdus |
| CONTENU | contenu | contenu | palgrí | FORTUNE | fortue | fortne | gemaes* |
| CULTURE | cultre | cultue | fondia | MACHINE | machne | machie | sorgou |
| DIGNITÉ | digtne | digtié | normau | COSTUME | costme | costue | mendai |
| HORLOGE | horlge | horloe | mantui | DIPLOMÉ | diplme | diplôe | genrau |
| VICTIME | victhe | victie | narsou | SYMBOLE | symble | symboe | burdai |
| VITRINE | vitrne | vittrie | colmau | BAGNOLE | bagnle | bagnoe | pezdi |
| BONJOUR | bonjur | bonjer | methis | SECTION | secton | sectin | gardul |
| BONSOIR | bonsir | bonsor | pamlet | GARDINN | garden | gardin | pulmos |
| LECTEUR | lectur | lecter | bongad | FACTEUR | factur | facter | molsin |
| NERVEUX | nervux | nervex | bachol | MONDIAL | mondal | mondil | verbut |
| SECTEUR | sectur | sectur | dalfin | MALHEUR | malurh | malher | cofnis |
| MANTEAU | mantéu | mantau | sufroi | MORCEAU | morceu | morcau | fulnoi |
| BALANCE | balçne | balonce | fodiru | MIRACLE | mircle | mirale | bento |
| CADAVRE | cadivre | cadare | soluni | DURABLE | durble | durale | vesigo |
| CAPABLE | capble | capale | tisuno | RACANTE | racnte | racote | simplu |
| VISIBLE | viable | visile | garuno | PENIBLE | pénble | pénile | fumato |
| VOLONTÉ | volnéte | voloté | muzaci | FACULTÉ | facilet | facuet | merodi |
| CAPITAL | capittl | capial | nomeur | HÔPITAL | hôpital | hôpial | vareud |
| DÉCISIF | décilf | décilf | logunt | DELICAT | délict | déliat | moguns |
| DÉFICIT | défict | défilt | palons | HABITER | habitr | habier | gomoul |
| DEVENIR | devnir | devoir | gazol | NATUREL | natrel | natuel | jochs |
| LIMITER | limttr | limiter | machon | DOMINE | domner | domier | sachut |
| MAGASIN | magsn | magain | gercou | CABINET | cabnet | cabiet | bordul |
| MATELAS | matels | mateas | vunord | ROBINET | robint | robit | camuld |
| POSITIF | positf | positf | camund | RELATIF | relatif | relaif | mibous |
| MALADIE | maldie | malale | bernou | FATIGUE | fatigue | fatuue | modrai |
| MUSIQUE | muisque | musiue | negato | LOGIQUE | loglqe | loguie | betani |
| MARIAGE | marige | mariae | voluna | DOMAINE | domine | domaie | begulo |
| SALAIRE | salire | salare | bonuda | SOLAIRE | soliire | solare | penugo |
| JUMEAUX | jumeax | jumeux | tados | CITOYEN | citoyn | citoen | resaud |
| DIAMANT | diamant | diamat | tuire | COUVERT | couvtr | couvet | maion |
| COUTURE | coutue | coutue | geisna | COURAGE | courge | courae | hellbo |
| CUISINE | cuisne | cuiuse | boelda | VOITURE | voitri | voitue | lauco |
| PAYSAGE | paysge | paysae | hedroï | QUALITÉ | qualité | qualié | boinsu |
| BOUQUET | bouquet | bouqut | paimon | SOUTIEN | souten | soutin | valiod |
| ARTISTE | artisne | articde | elbugo | ARTICLE | article | artille | onsusdi |

* Not matched in CV structure.
### Appendix 2

**Nonword targets and the corresponding nonword primes tested in Experiment 1**

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<tr>
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<td>fiochg</td>
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<td>paeud</td>
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</thead>
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<tr>
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<tr>
<td>Target</td>
</tr>
</tbody>
</table>

| CADRIEM | cadreim | cadrim | gosuln |
| ZARDEIN | zardin | zarden | buchot |
| GSVRIOT | gevrot | gevrot | madlun |
| NARTIUL | nartil | nartul | ceapog |
| FURTAIM | furtim | furtam | zondel |
| MAILOUR | mailor | mailur | veudas |
| GAIROUL | gairol | gairul | nuedac |
| JUINVER | juinvr | juinver | destol |
| CHOLAIN | cholan | cholin | bruget |
| UVIPLIT | uviplit | uviplit | eborac |
| MODRAUL | modral | modrol | hespin |
| COINTER | cointir | coiner | juenal |
| MICHONT | michnt | michot | lavrec |
| HULDONS | huldos | huldn | gabrit |
| HARZOL | harzol | harzil | budgen |
| FRIGONT | frignt | frigot | slubam |
| COLFAME | colfae | colfme | nudroi |
| PALNOUD | palnol | palnod | osteif |
| MUTILE | murtl | murtle | bachno |
| ZOLDREN | zoldrn | zoldin | pascet |
| TROLAIN | trölin | trölan | spauv |
| BRINEU | brinud | brined | thogam |
| MOUCHE | moucht | moucet | lieban |
| VOSELFRED | voslred | voslrd | bunget |
| HELOR | helorig | helorg | unamp |
| VREMOIS | vremos | vremis | bladun |
| POIREUL | poreul | poriul | muhat |
| SUITREL | suitrel | suitel | geoam |
| GOLMARD | golmad | golmar | lestin |
| BONGAL | bongal | bongil | hemdut |
| PORTAIL | porlia | porial | cugnet |
| BALIVER | baliver | balier | nuchod |
| SOILGAR | soilgr | soilet | neaud |
| ONTEGES | onteg | onteis | imavut |
| STURIOL | stuiol | sturol | cheman |
| DRAGUME | dragme | drame | glosni |
| JOLRAIN | jolrin | jolran | humlet |
| TRUDINT | trudit | trudnt | chelam |
| BAIACEL | baiacel | baiacel | thons |
| SLUOMCH | slumch | slumoh | branet |
| STUIGL | stuigl | stuigl | choarm |
| DOMCHAR | domchr | doncar | bungus |
### Appendix 3

Word targets and the corresponding transposed letter, orthographic control, and unrelated primes tested in Experiments 3 and 4

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